What theorists want to see with S-PHENIX

Abhijit Majumder
Wayne State University

S-PHENIX Inaugural meeting, Rutgers University,

What a theorist wants to see with S-PHENIX

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Outline

- Where are we (jet theory) right now
- Where do we want to be by the start of S-PHENIX
- What can we learn from S-PHENIX
- What needs to happen for theory to succeed by the time S-PHENIX turns on

Virtuality: the jet's multi-scale probe

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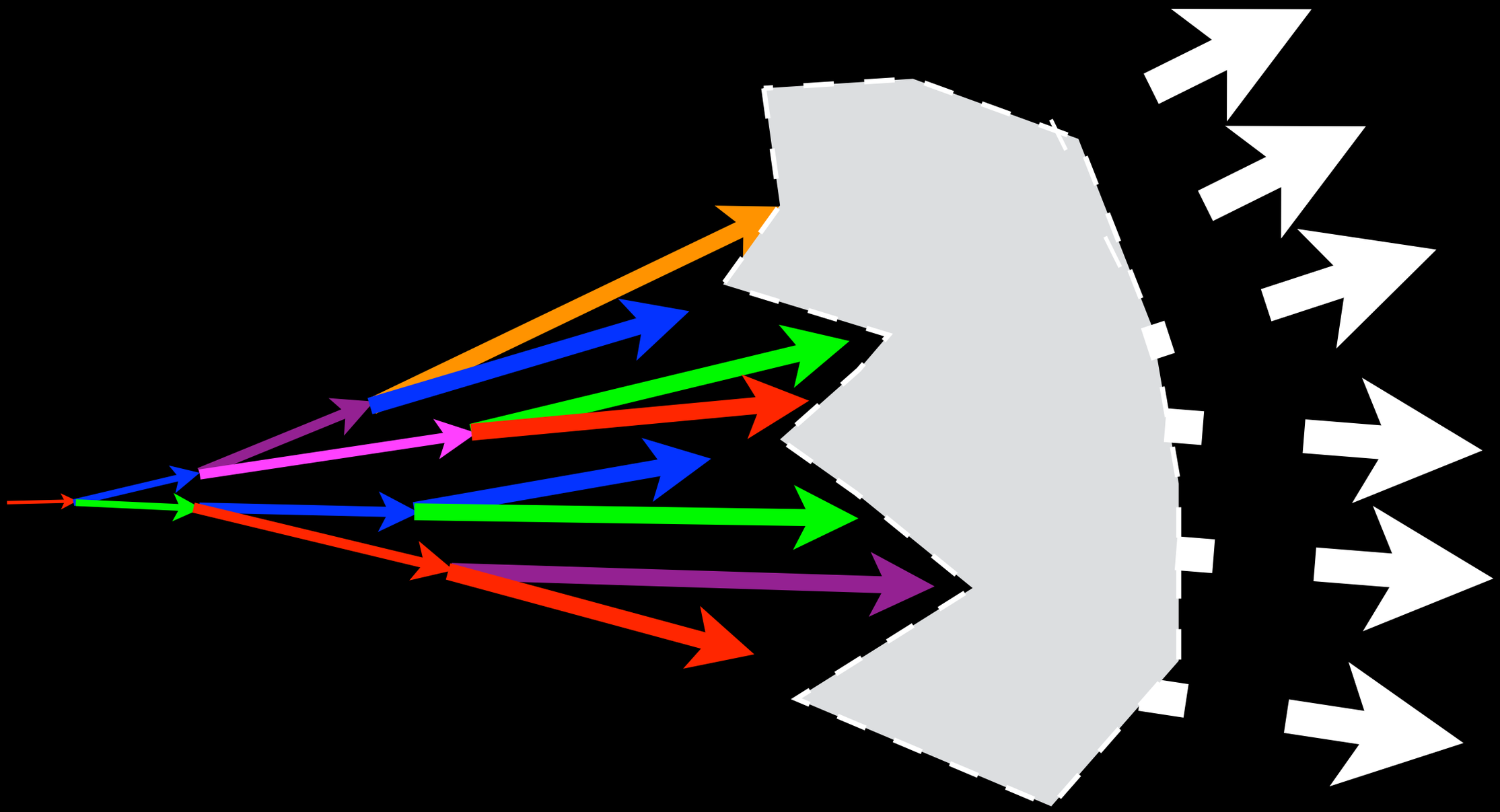

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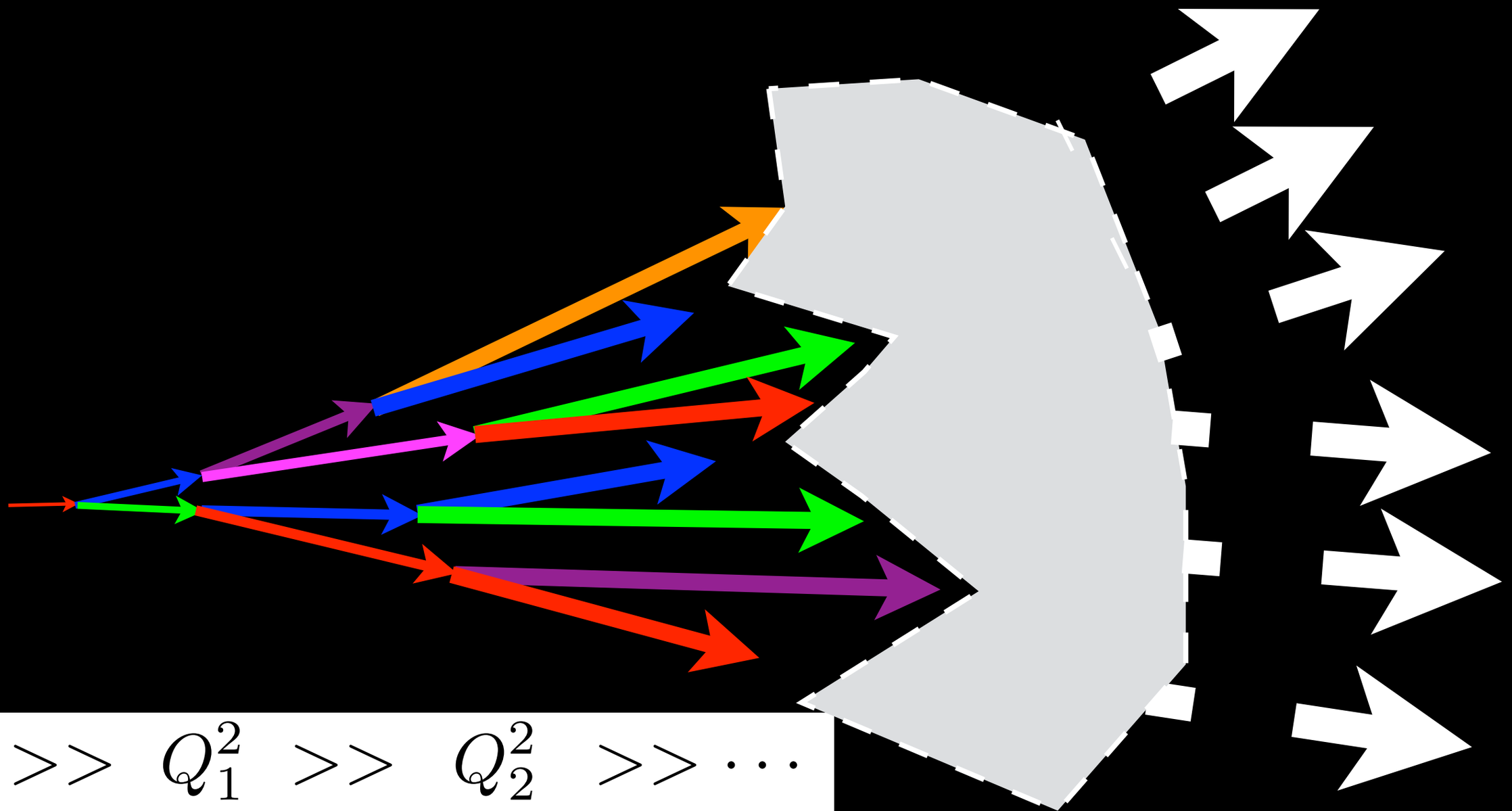

$$Q_0^2 >> Q_1^2 >> Q_2^2 >> \cdots$$
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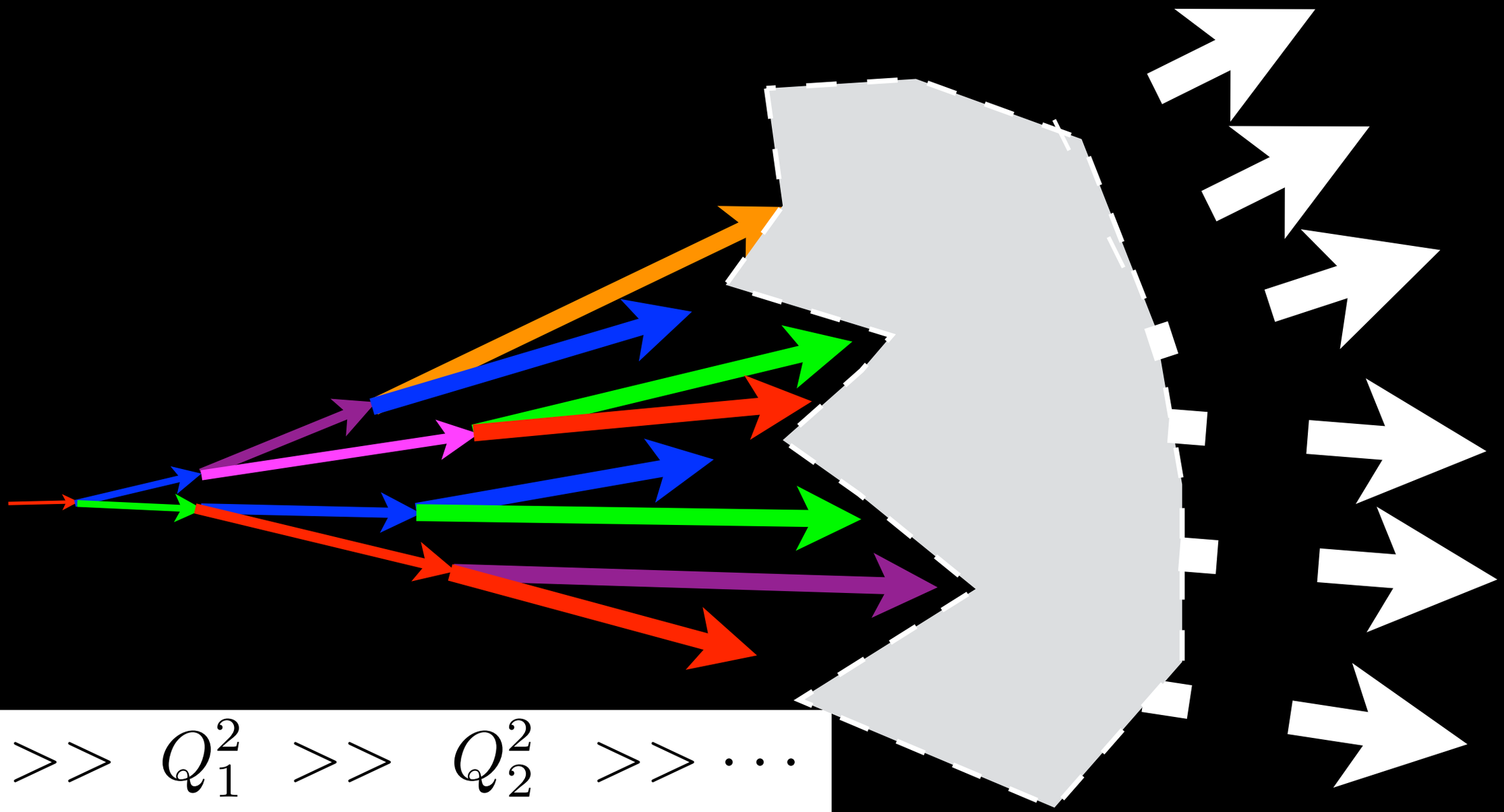

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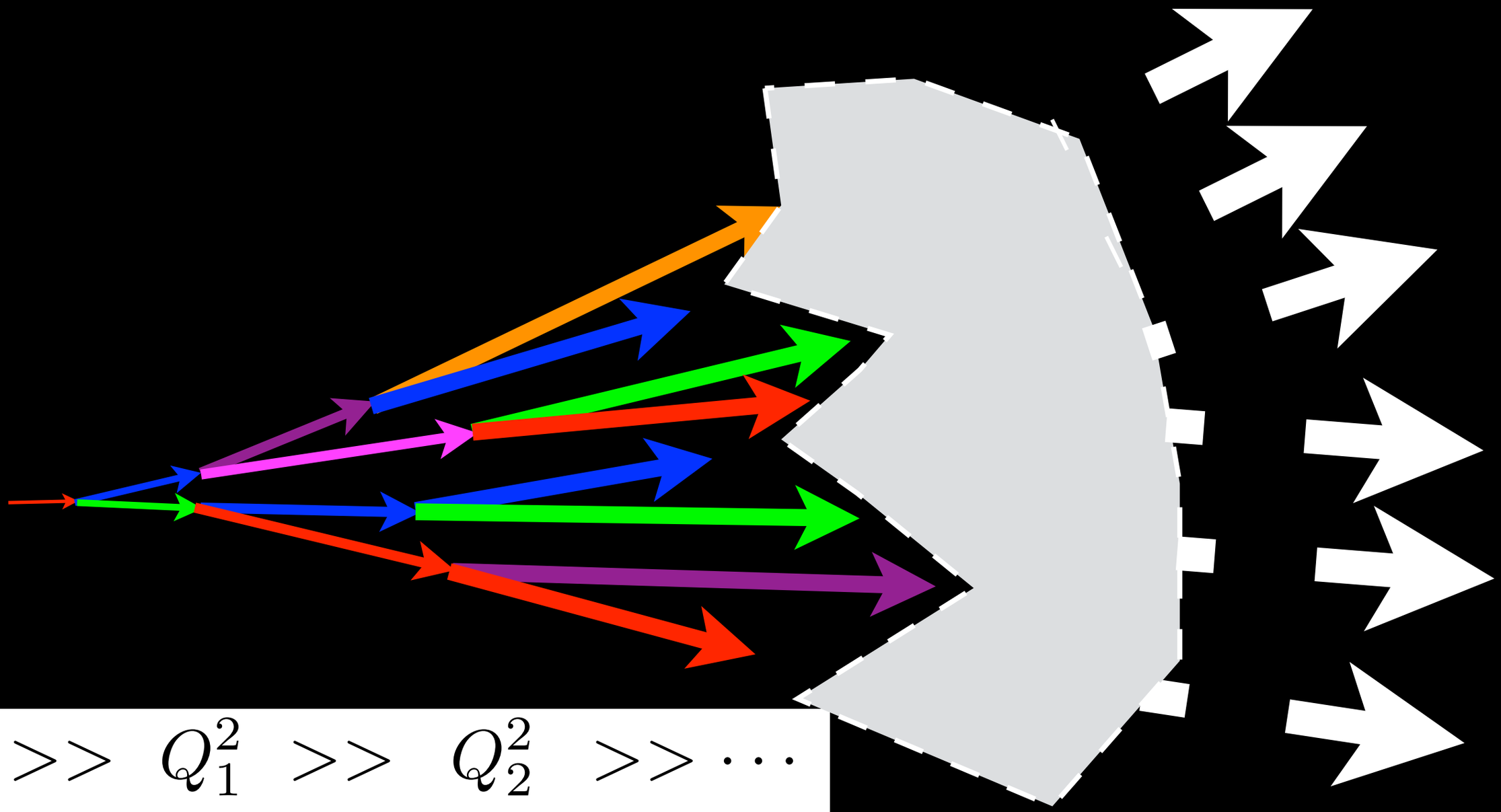

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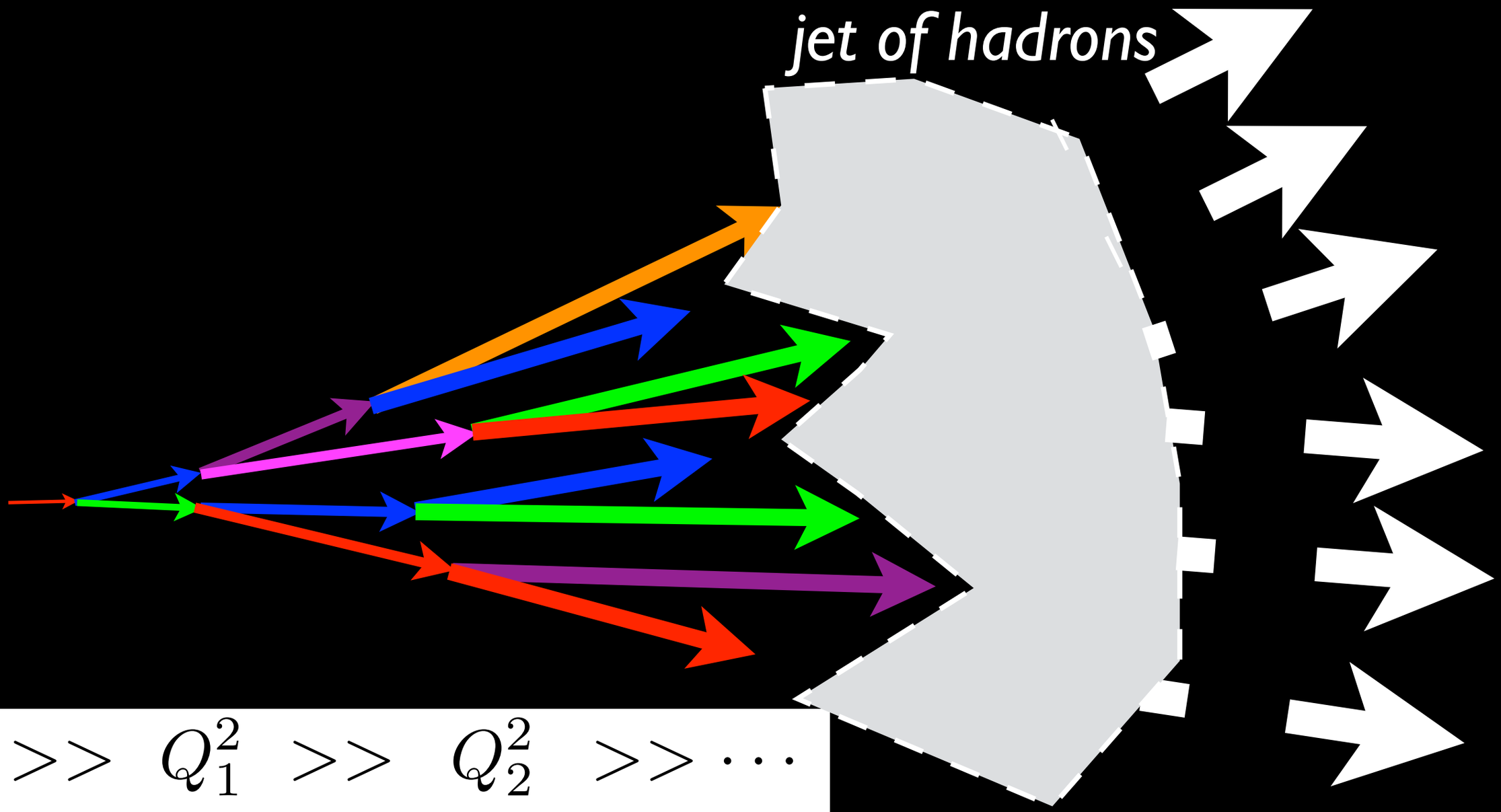

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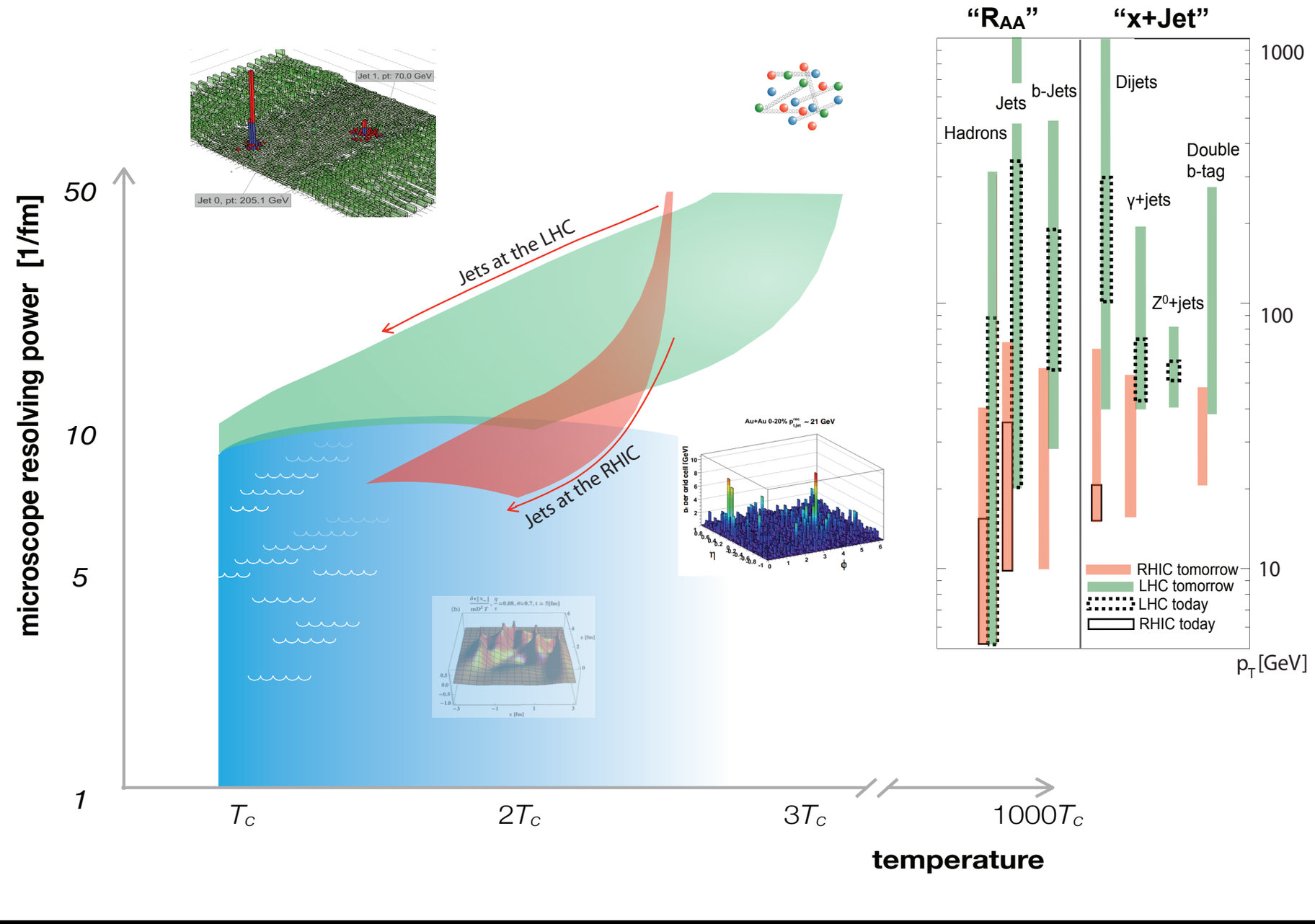
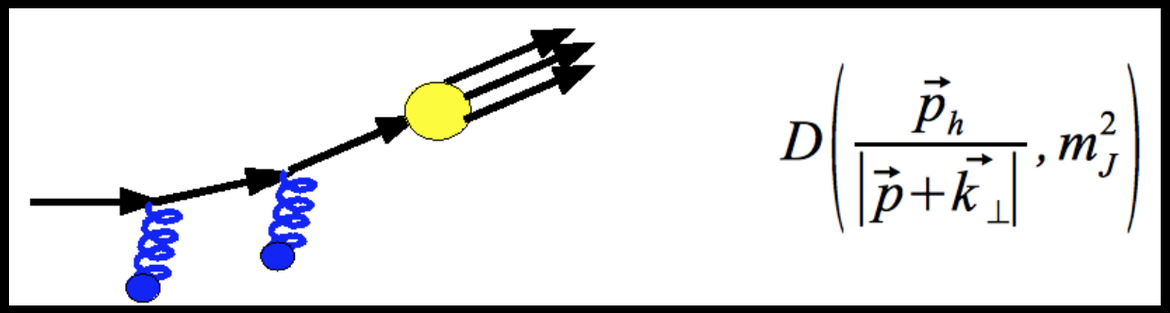
Concept captured by S-PHENIX & QCD white paper



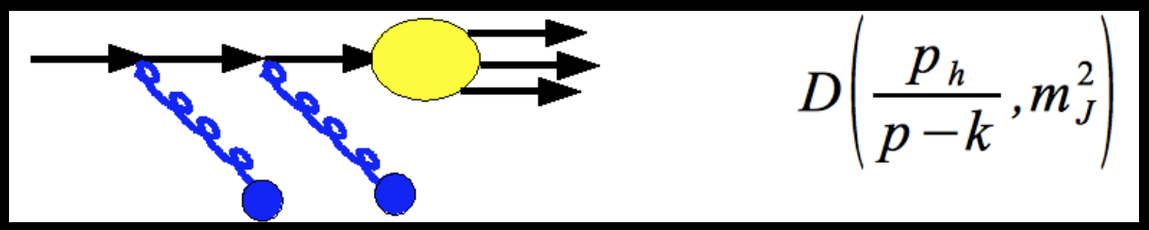
At high resolution,
transport coefficients for near on-shell partons

$$p_z^2 \simeq E^2 - p_\perp^2 \qquad\qquad p^+ \simeq p_\perp^2 / 2p^-$$



$$\hat{q} = \frac{\langle p_\perp^2 \rangle_L}{L}$$

Transverse momentum diffusion rate



$$\hat{e} = \frac{\langle \Delta E \rangle_L}{L}$$

Elastic energy loss rate also diffusion rate e_2

By definition, describe how the medium modifies the jet parton!

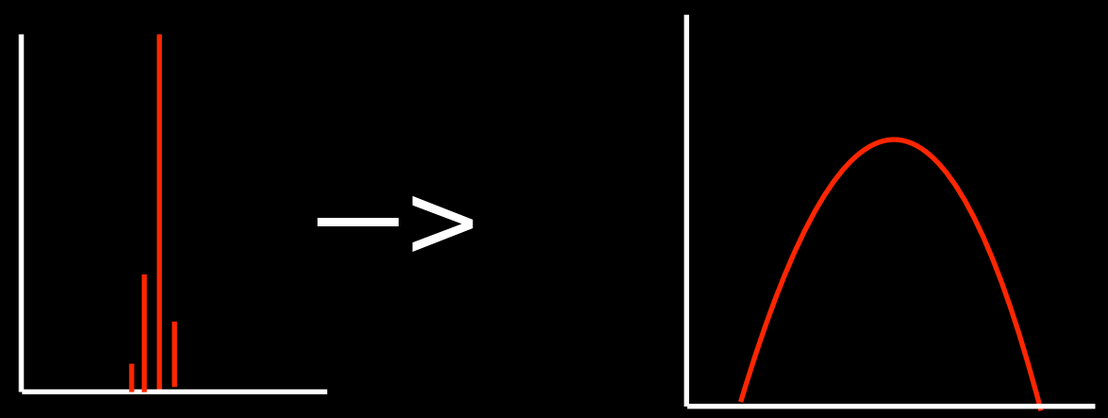
In general, 2 kinds of transport coefficients

Type 1: which quantify how the medium changes the jet

$$\hat{q}(E, Q^2) \qquad \hat{q}_4(E, Q^2) = \frac{\langle p_T^4 \rangle - \langle p_T^2 \rangle^2}{L} \dots$$

$$\hat{e}(E, Q^2) \qquad \hat{e}_2(E, Q^2) = \frac{\langle \delta E^2 \rangle}{L} \qquad \hat{e}_4(E, Q^2) = \frac{\langle \delta E^4 \rangle - \langle \delta E^2 \rangle^2}{L} \dots$$

Type 2: which quantify the space-time structure of the deposited energy momentum at the hydro scale

$\delta T^{\mu\nu}$ 

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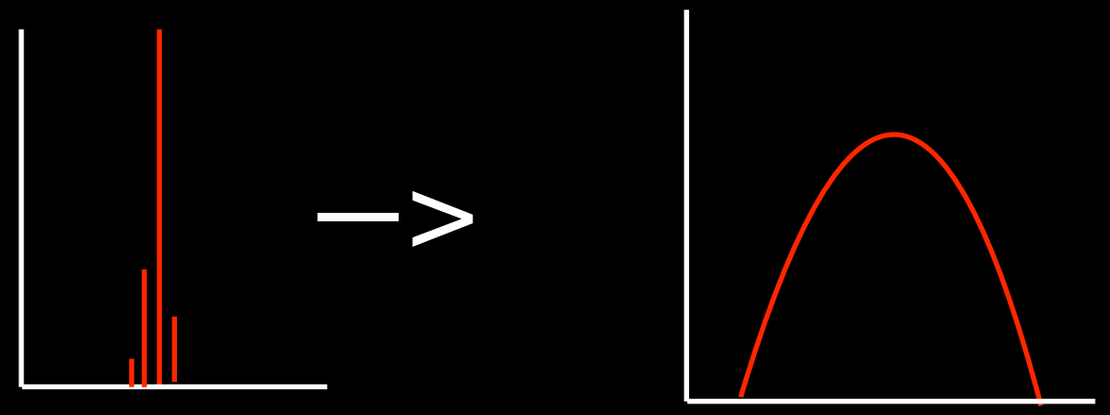
$\delta T^{\mu\nu}$ 

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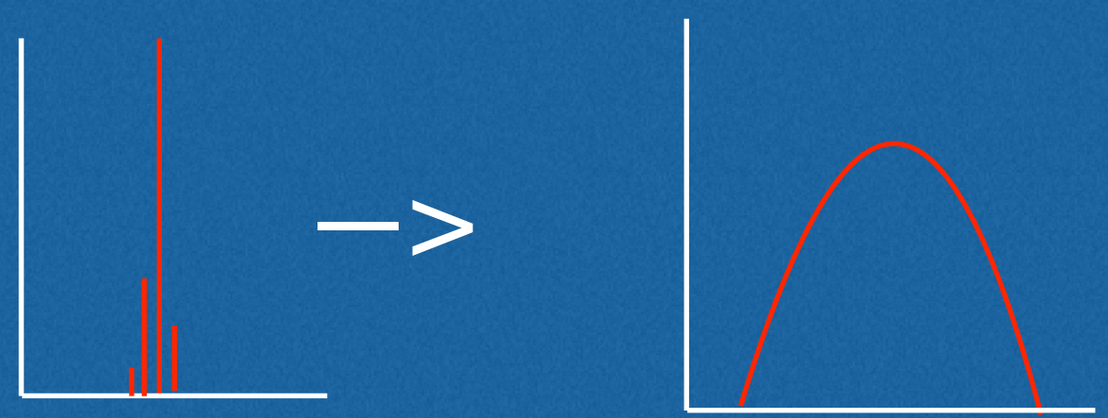

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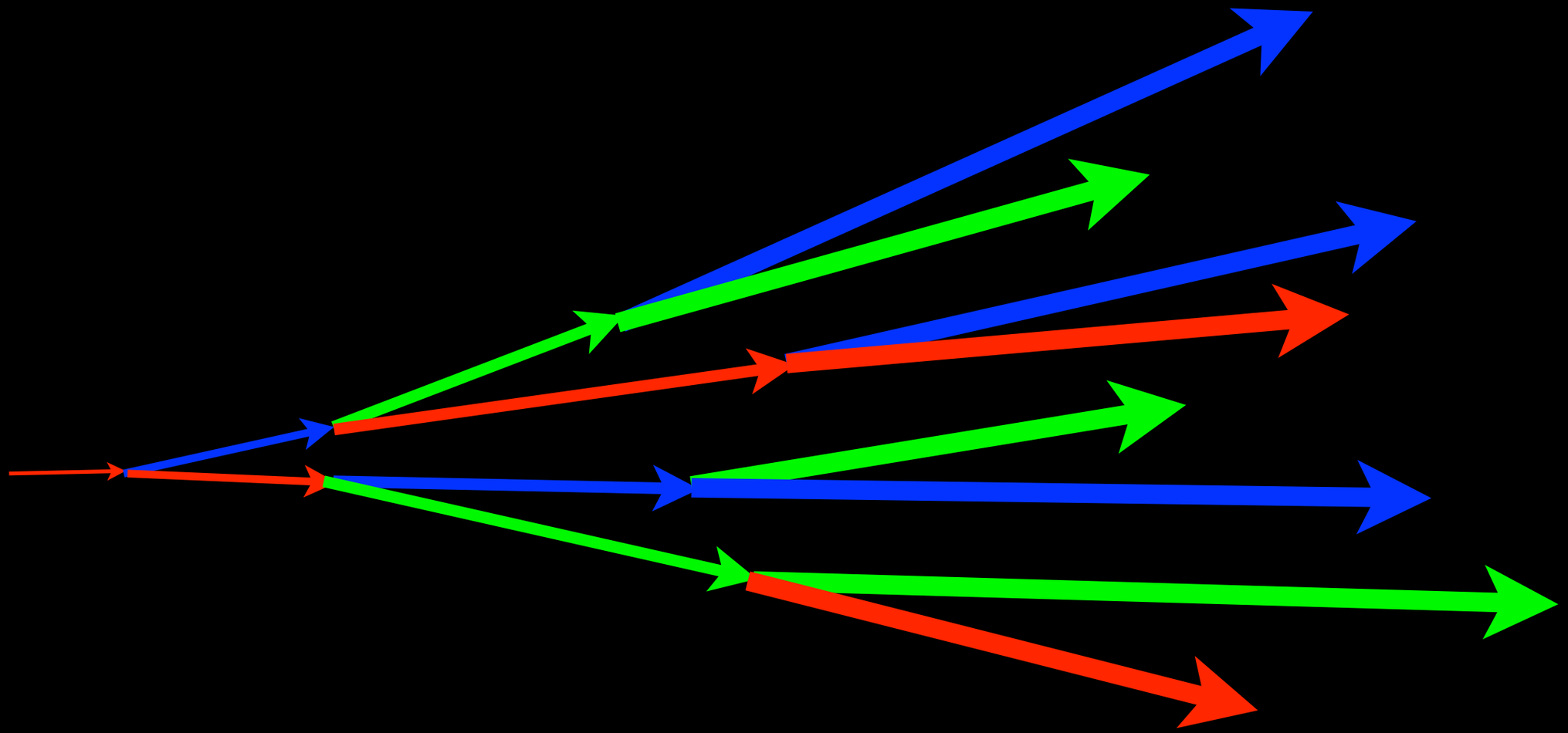

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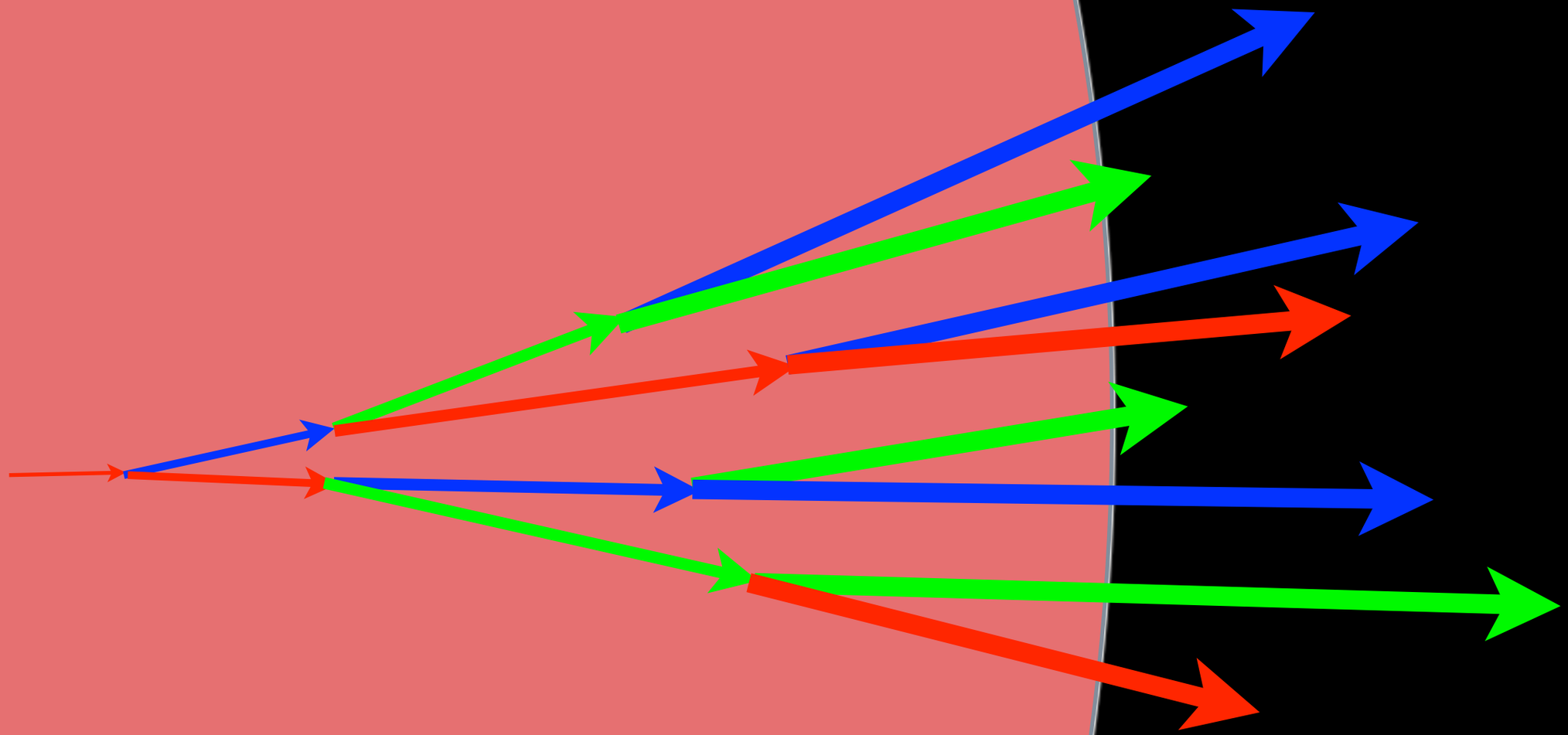

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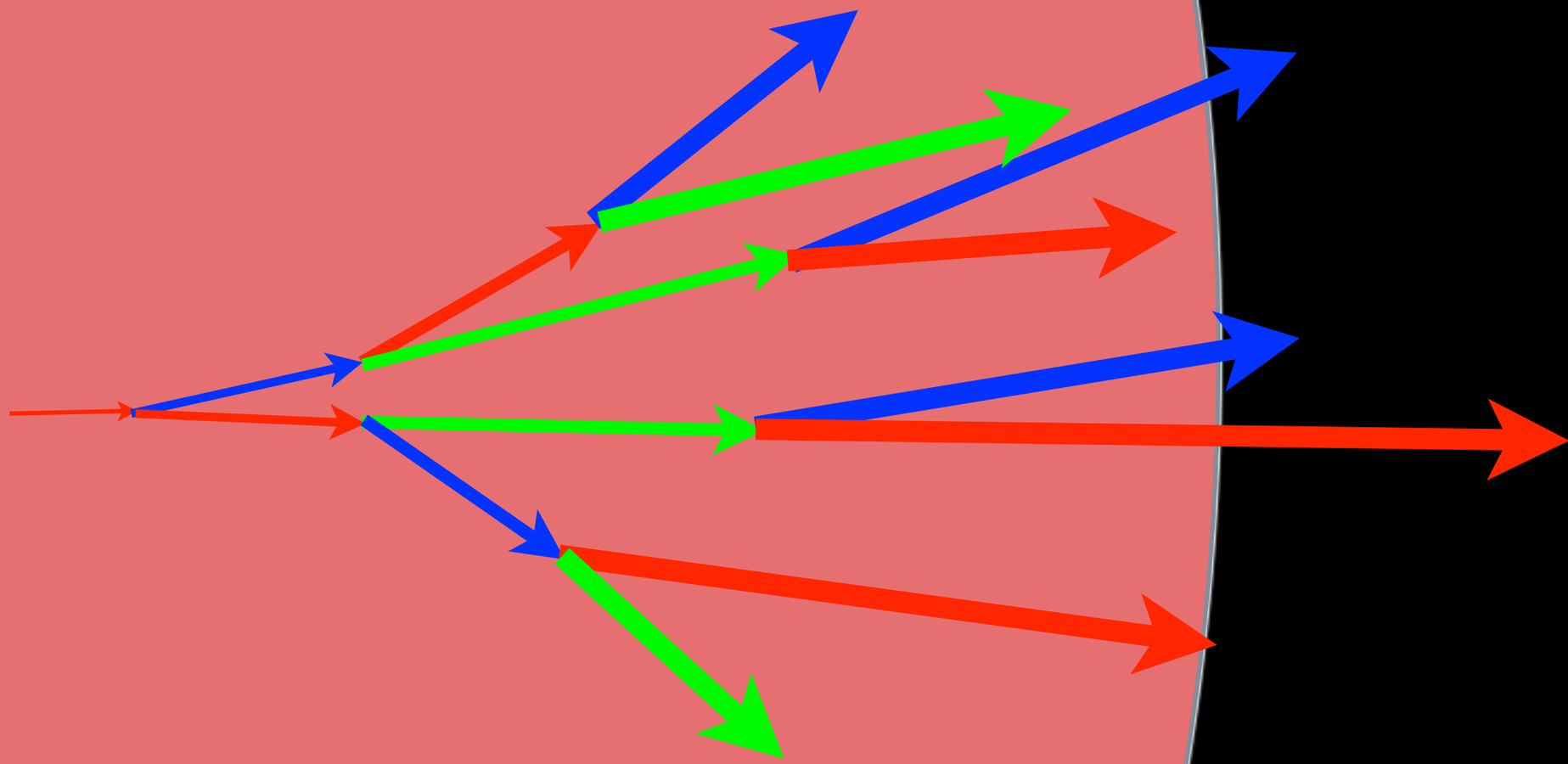

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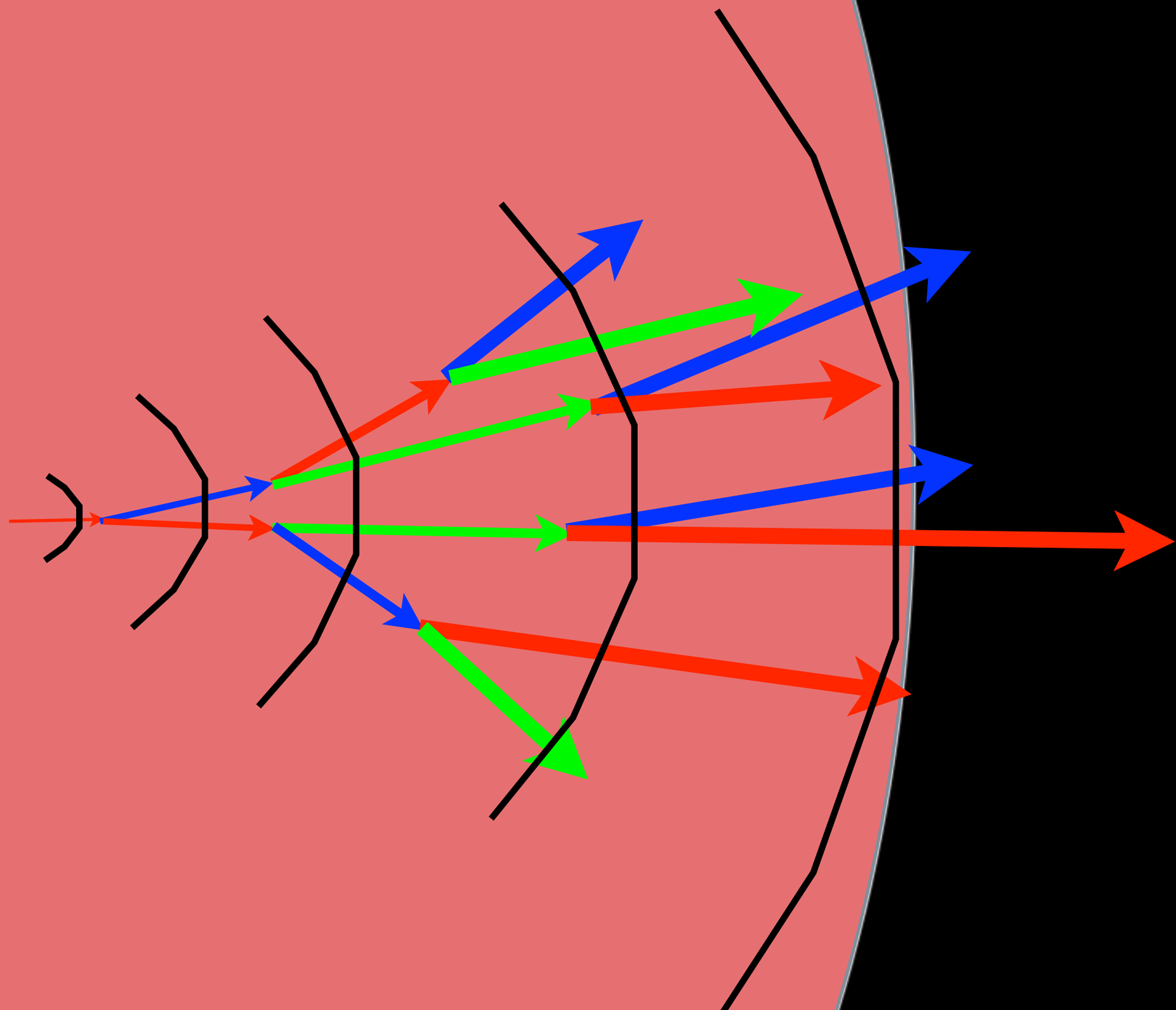

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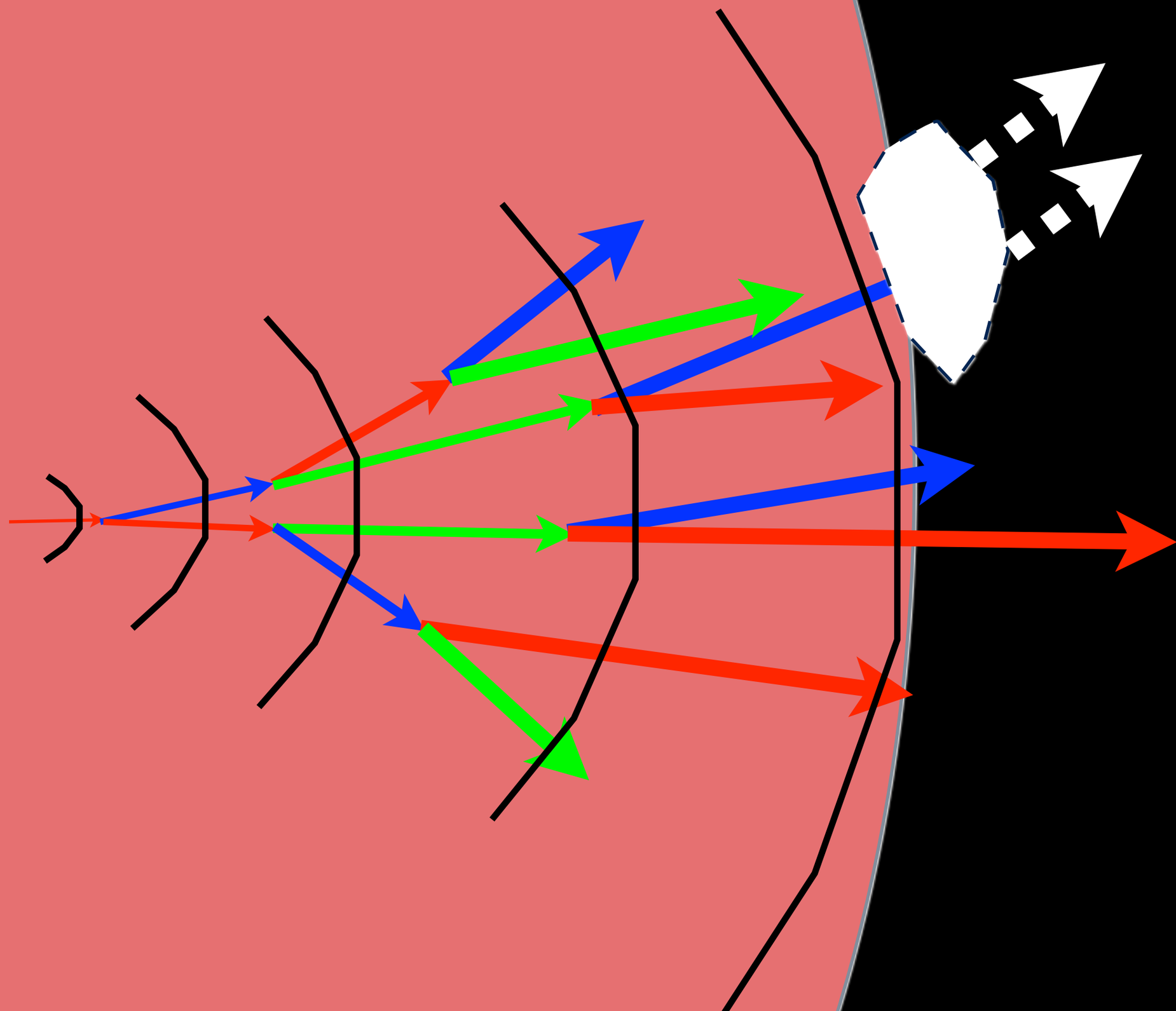

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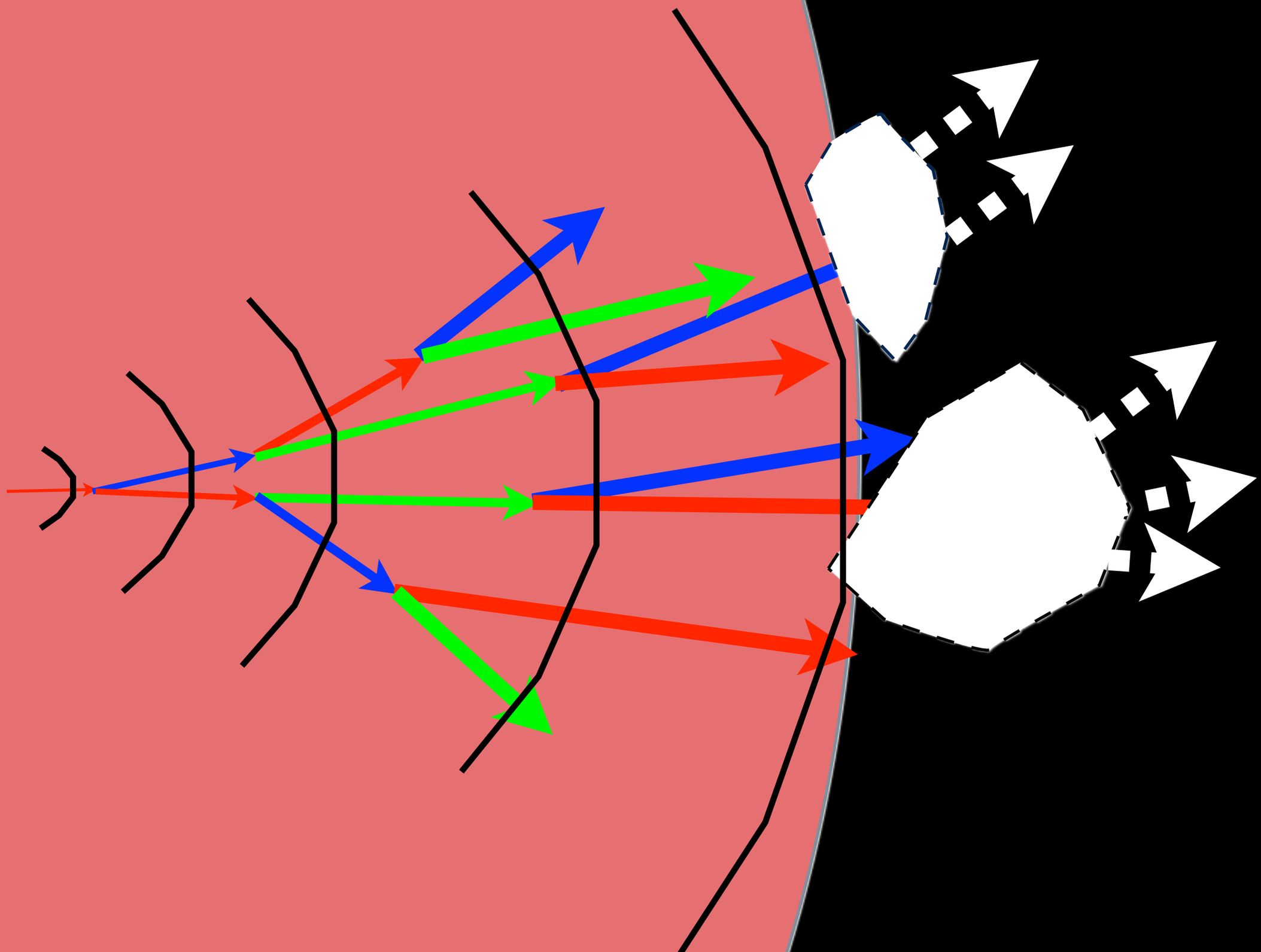
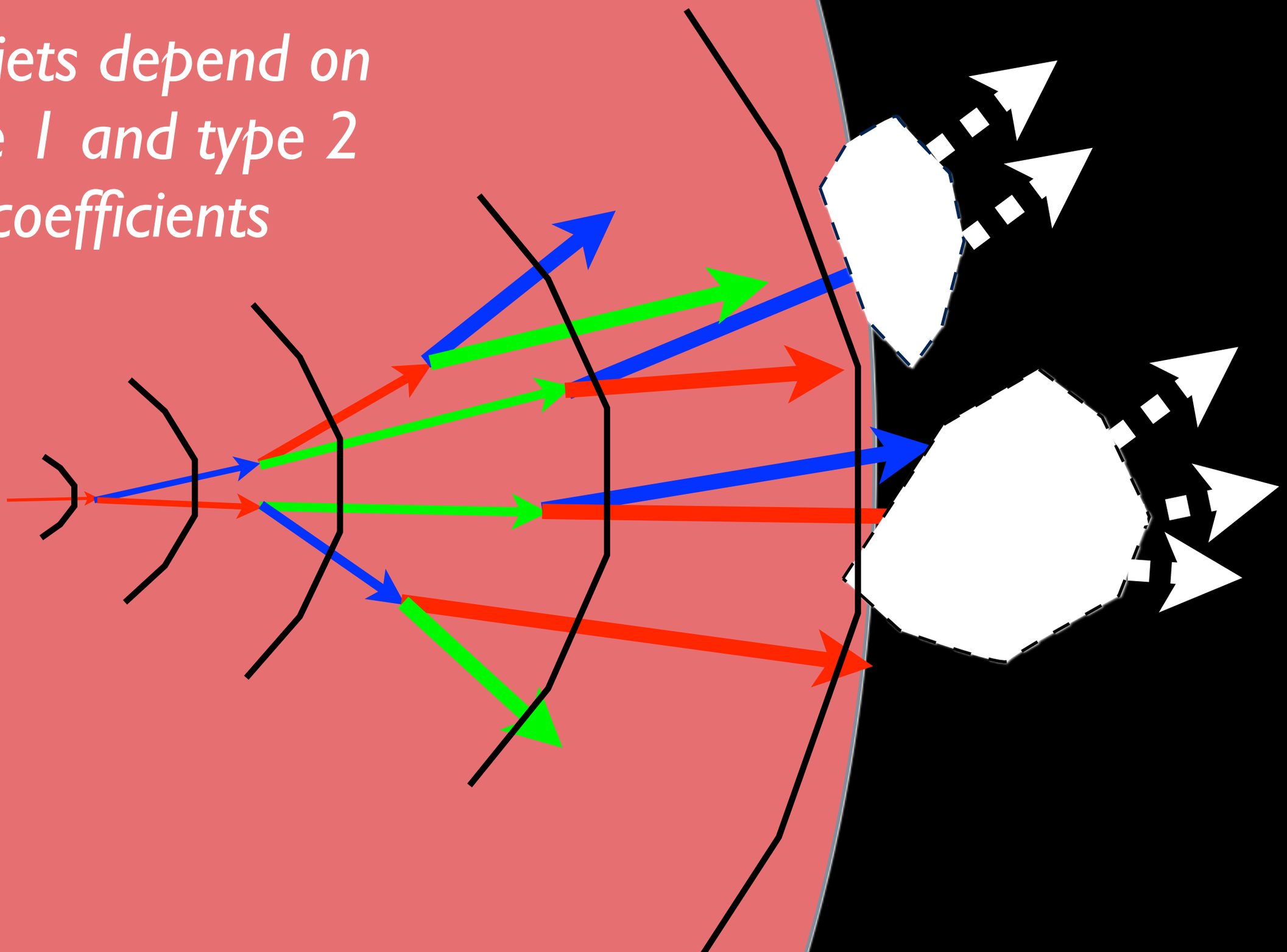
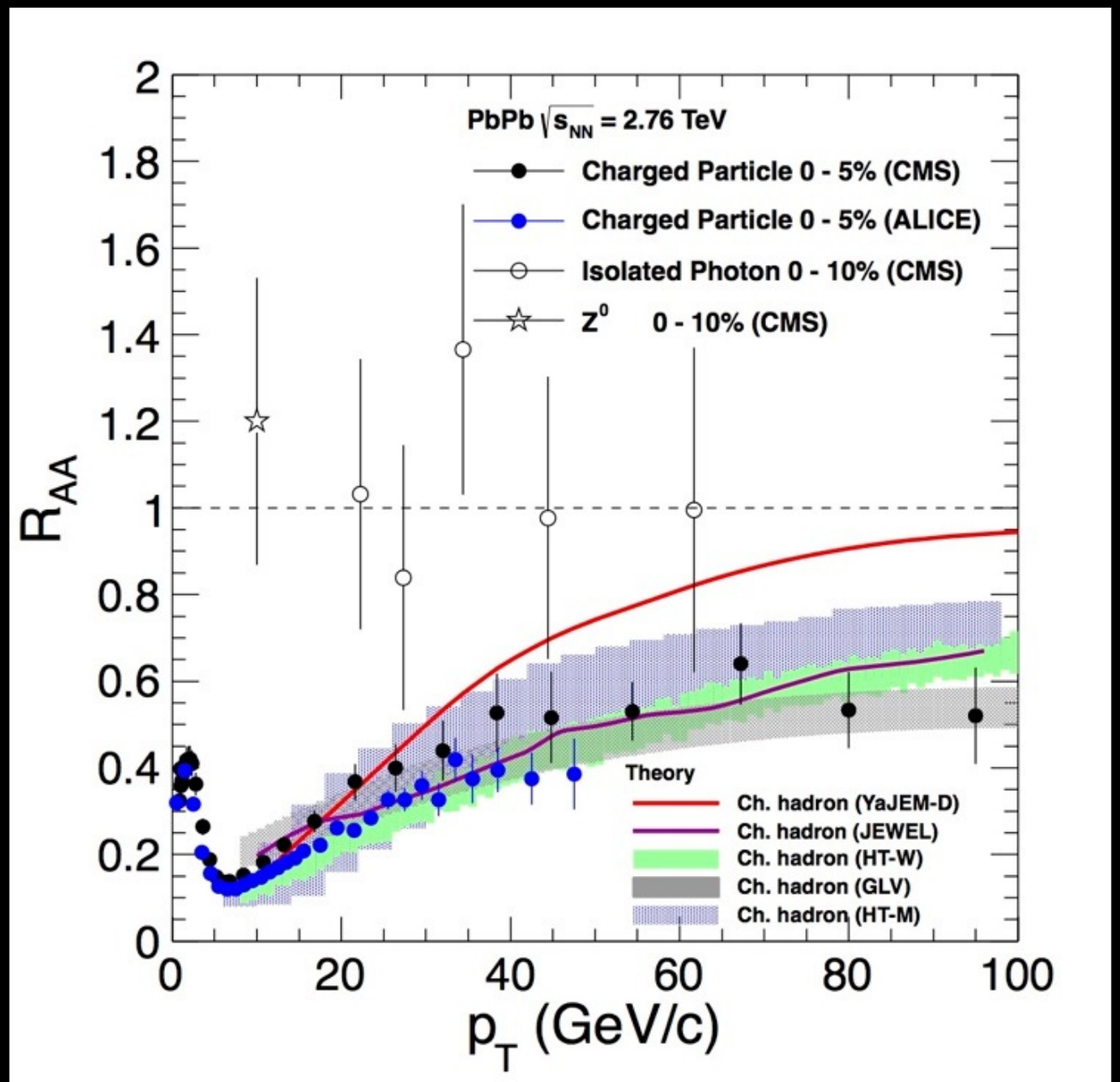


To get all these coefficients, need full jets

Full jets depend on type 1 and type 2 coefficients



There are observables that are only sensitive to type I



- *Focussing on the highest energy part of the jet,*
- *Leading hadron analysis, di-hadrons,*
- *Once type 1 coefficients are established, can then use that to deduce type 2 coefficients…*

Seems to require a $q = 1 - 2$ GeV^2/fm. at top RHIC Temperature

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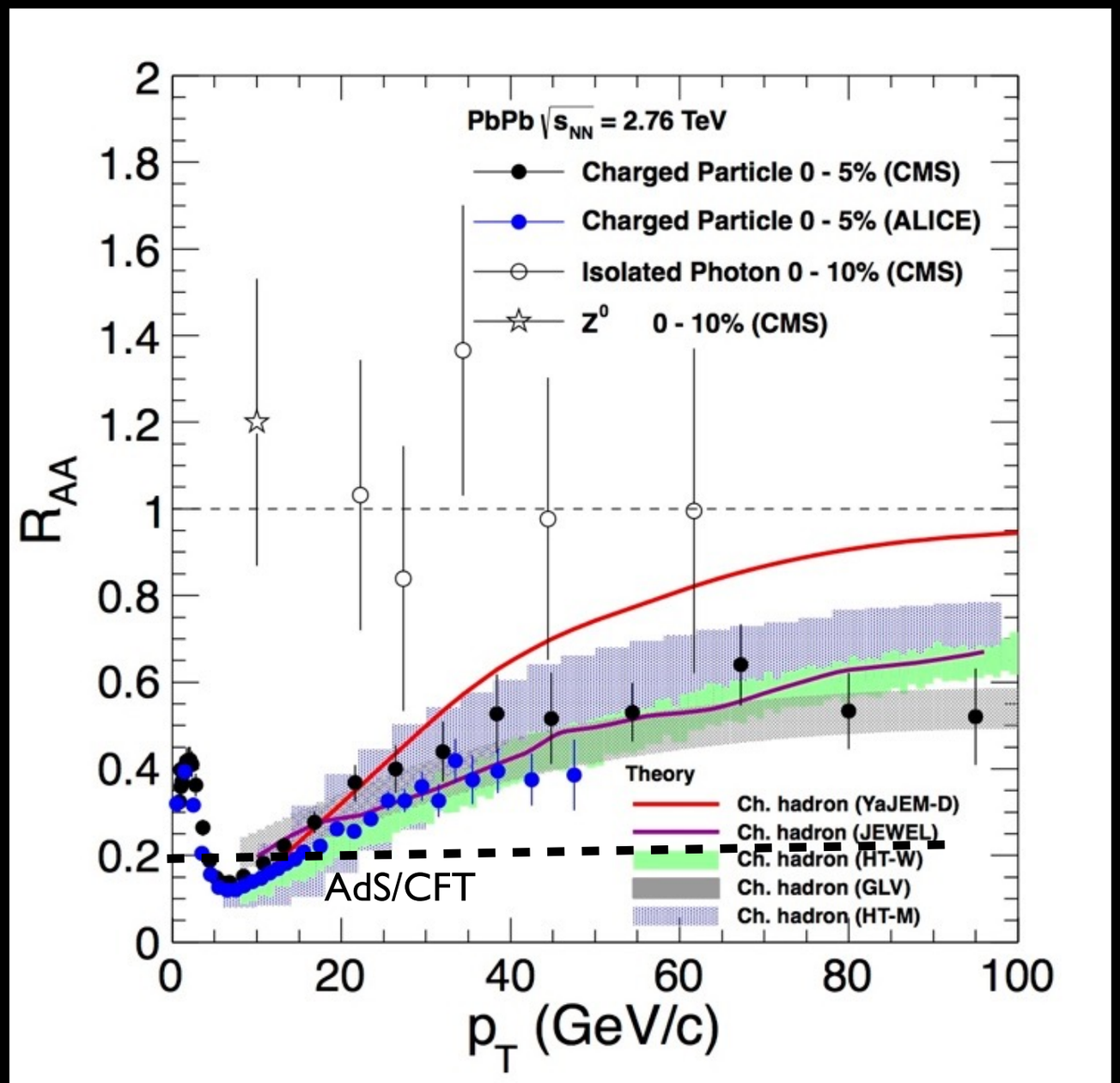

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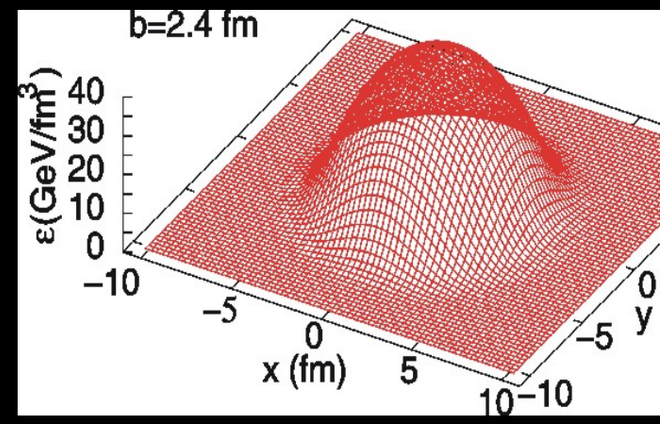
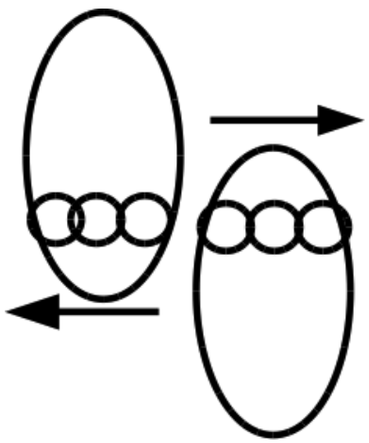
In all calculations (unless stated otherwise) bulk medium described by viscous fluid dynamics



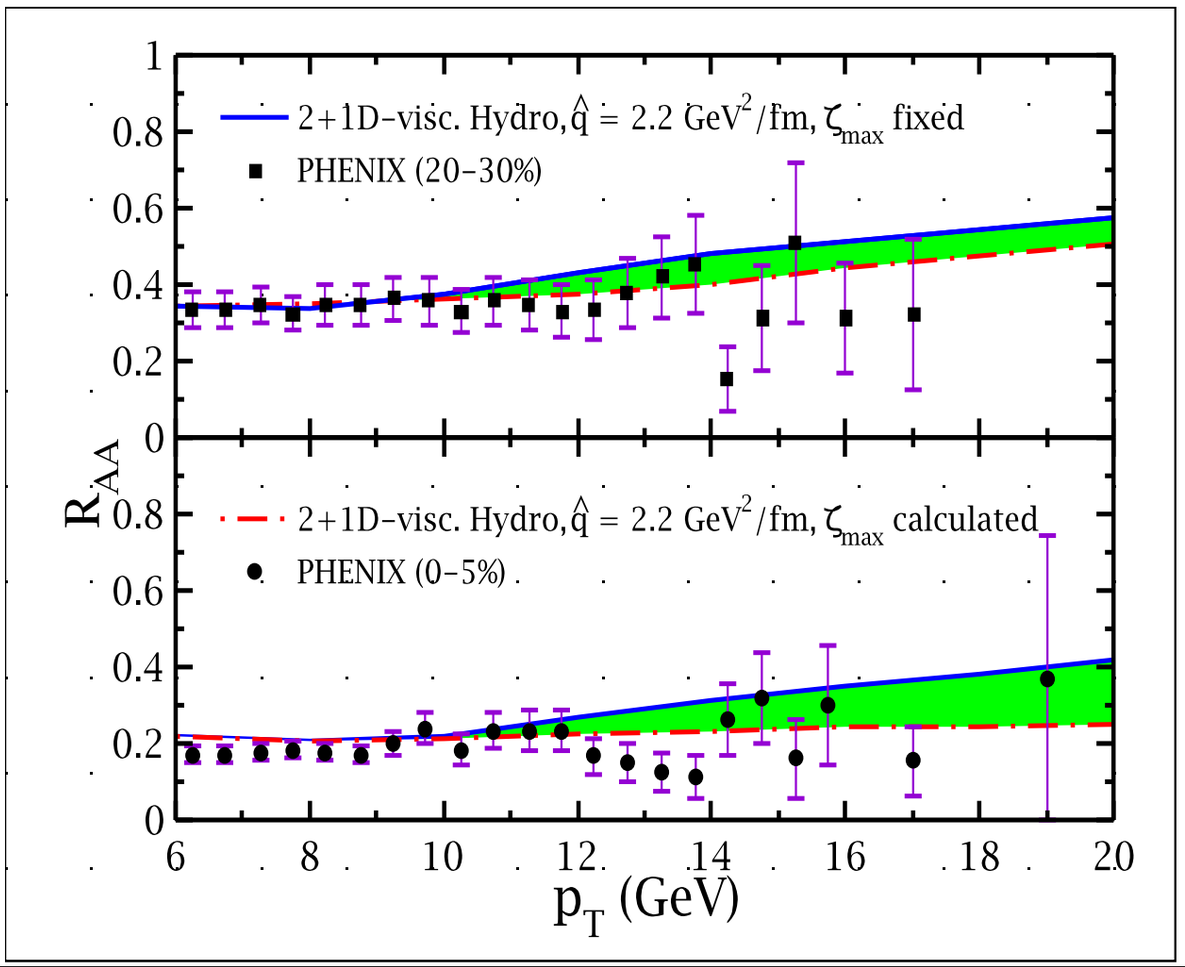
Medium evolves hydro-dynamically as the jet moves through it
Fit the $\hat{q}$ for the initial T in the hydro in central coll.



$$\hat{q}(\vec{r},t) = \hat{q}_0 \frac{s(\vec{r},t)}{s_0}$$

$$s_0 = s(T_0)$$

$$R_{AA} \sim \frac{\frac{dN_{AA}}{dp_T dy}}{N_{bin}\frac{dN_{pp}}{dp_T dy}}$$



A problem with the extracted coefficient

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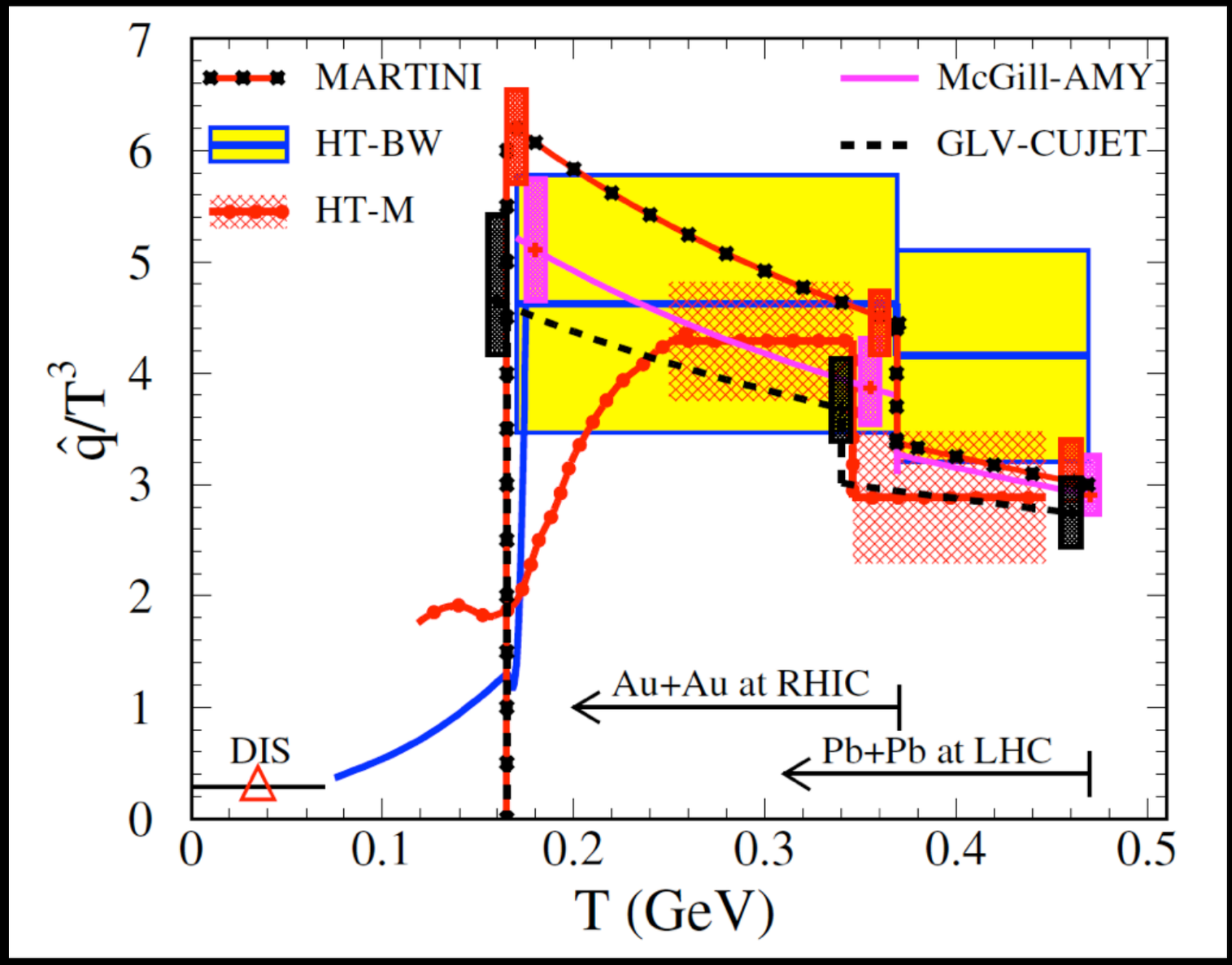

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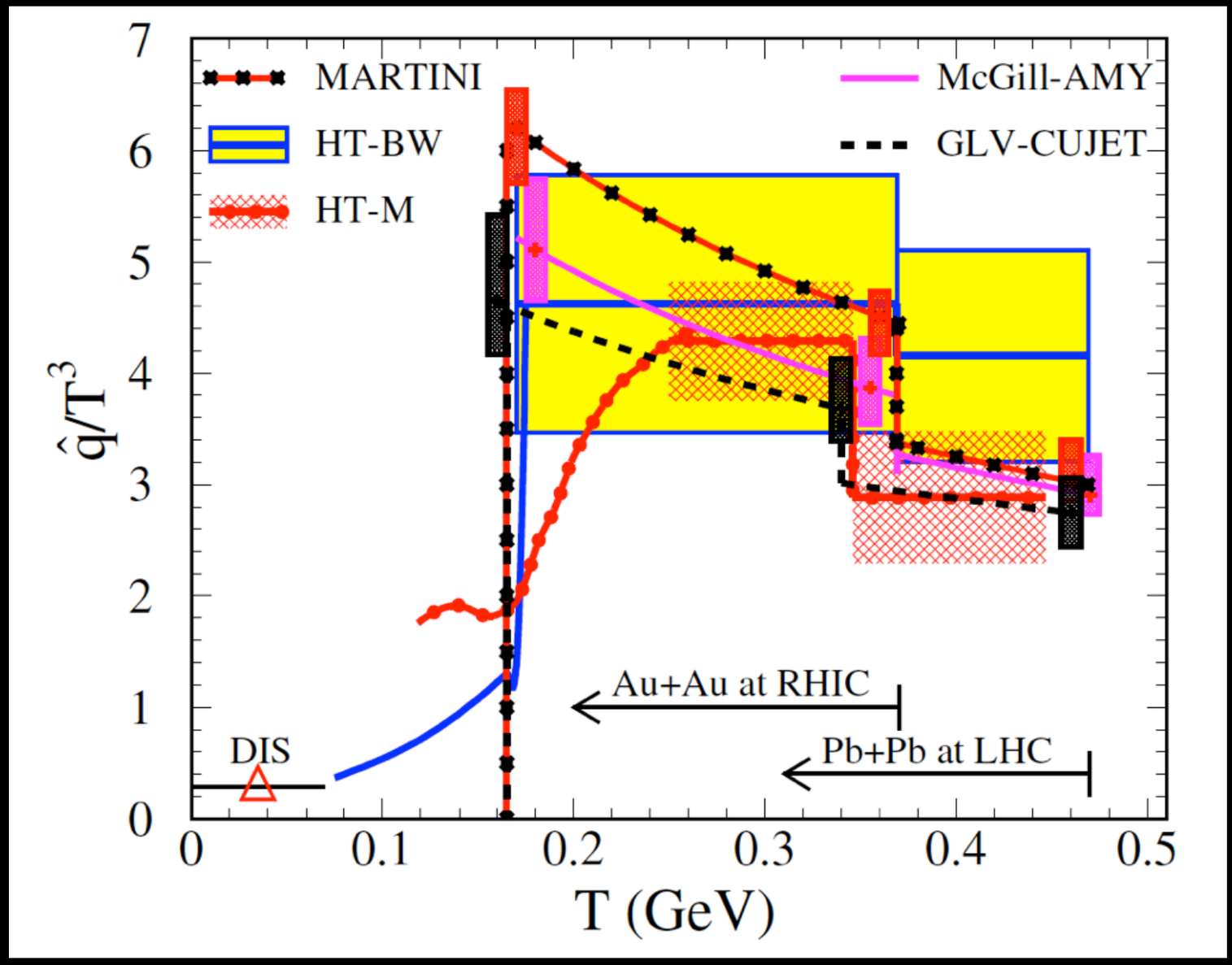
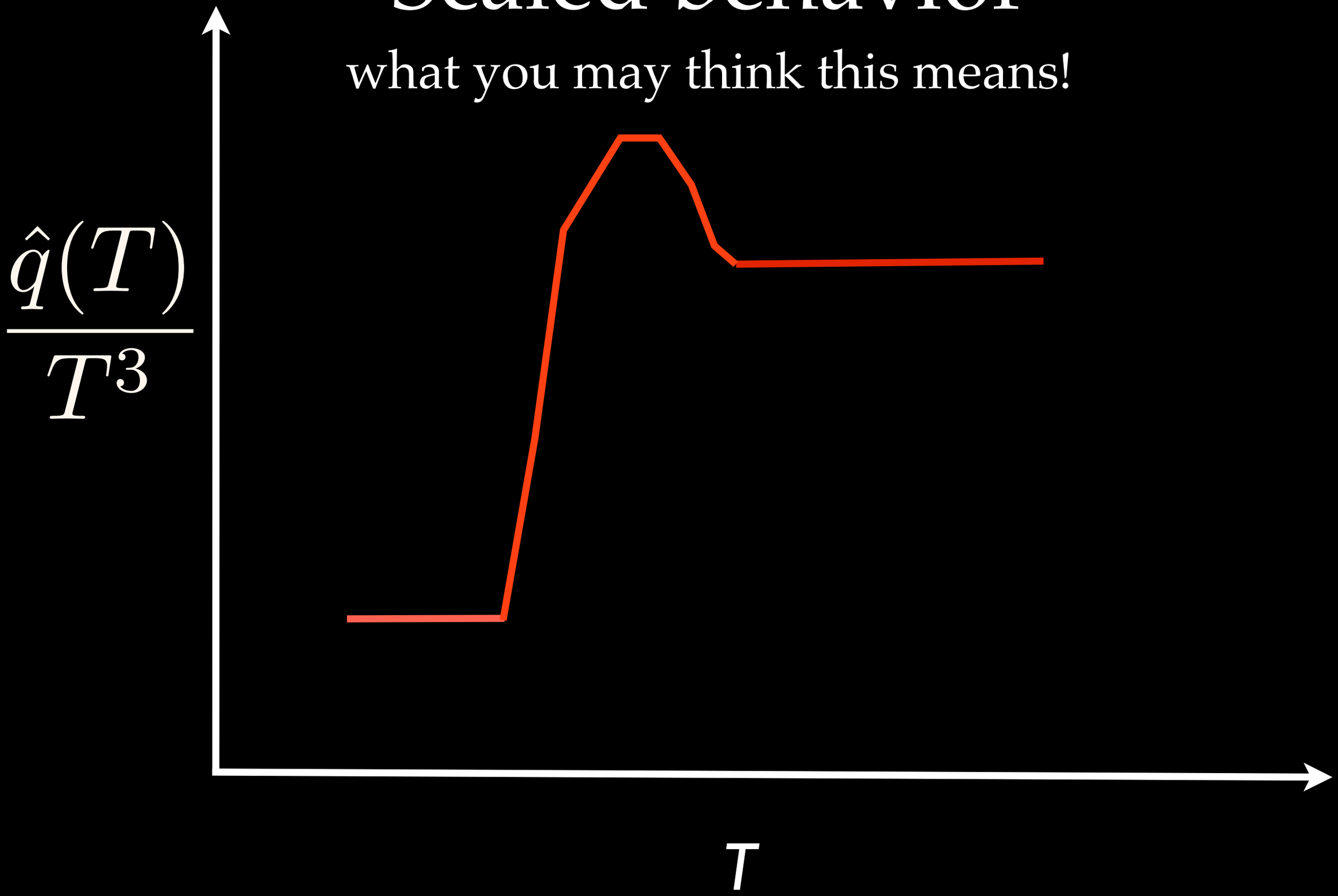


K. Burke et al.

Scaled behavior

what you may think this means!



Definition of $\hat{q}$: in a thermal bath

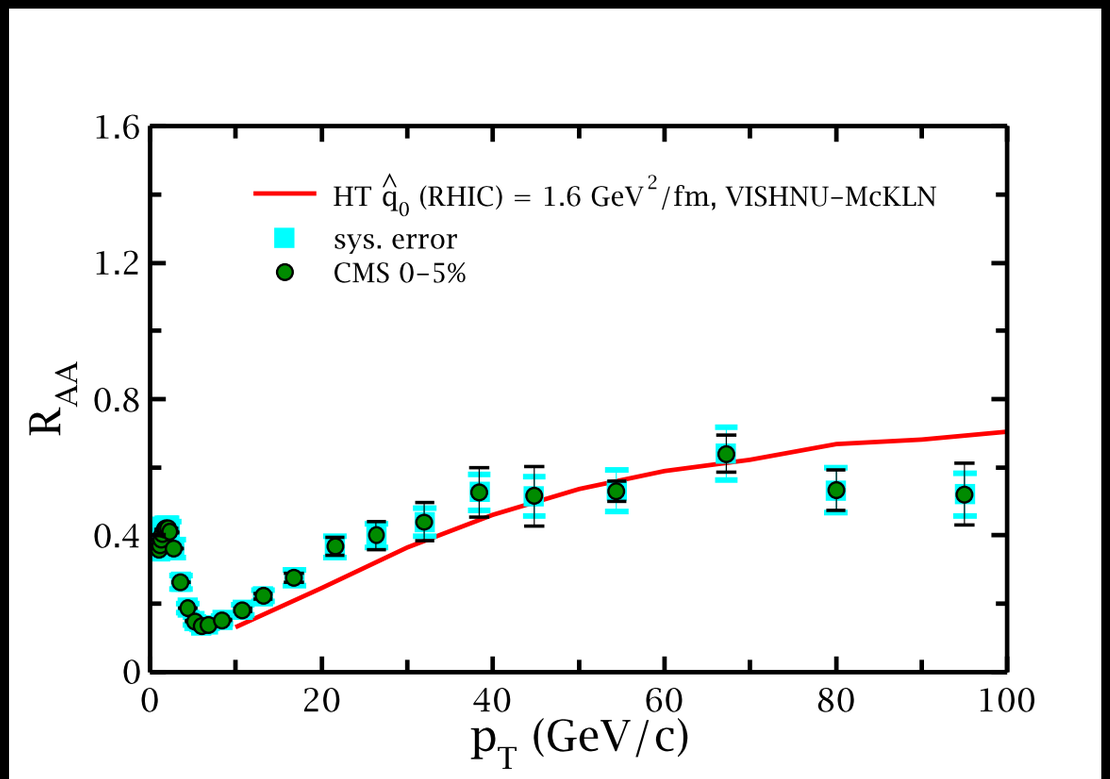
$$\hat{q} = \frac{4\pi^2\alpha_s}{N_c}\int \frac{dy^- d^2y_\perp}{(2\pi)^3} d^2k_\perp e^{-i\frac{k_\perp^2}{2q^-}\cdot y^- + i\vec{k}_\perp\cdot\vec{y_\perp}}$$

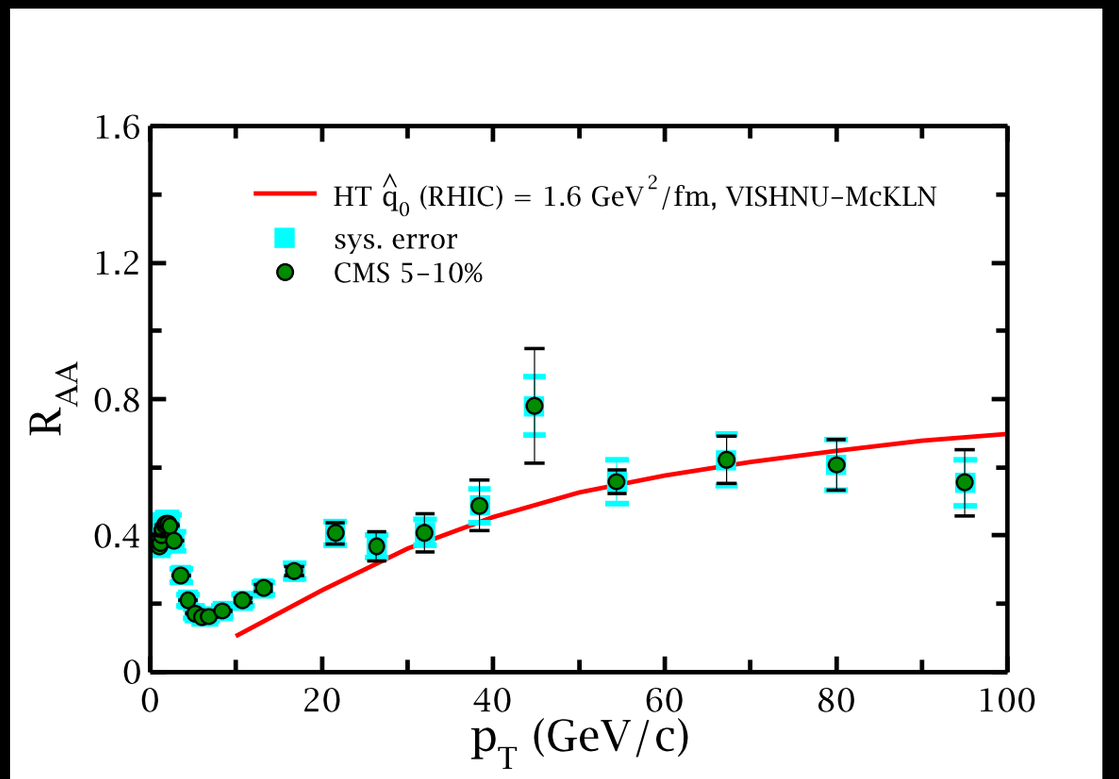
$$\langle n|\frac{e^{-\beta E_n}}{Z} F^{+,}{}_\perp(y^-)F_\perp^+(0)|n\rangle$$

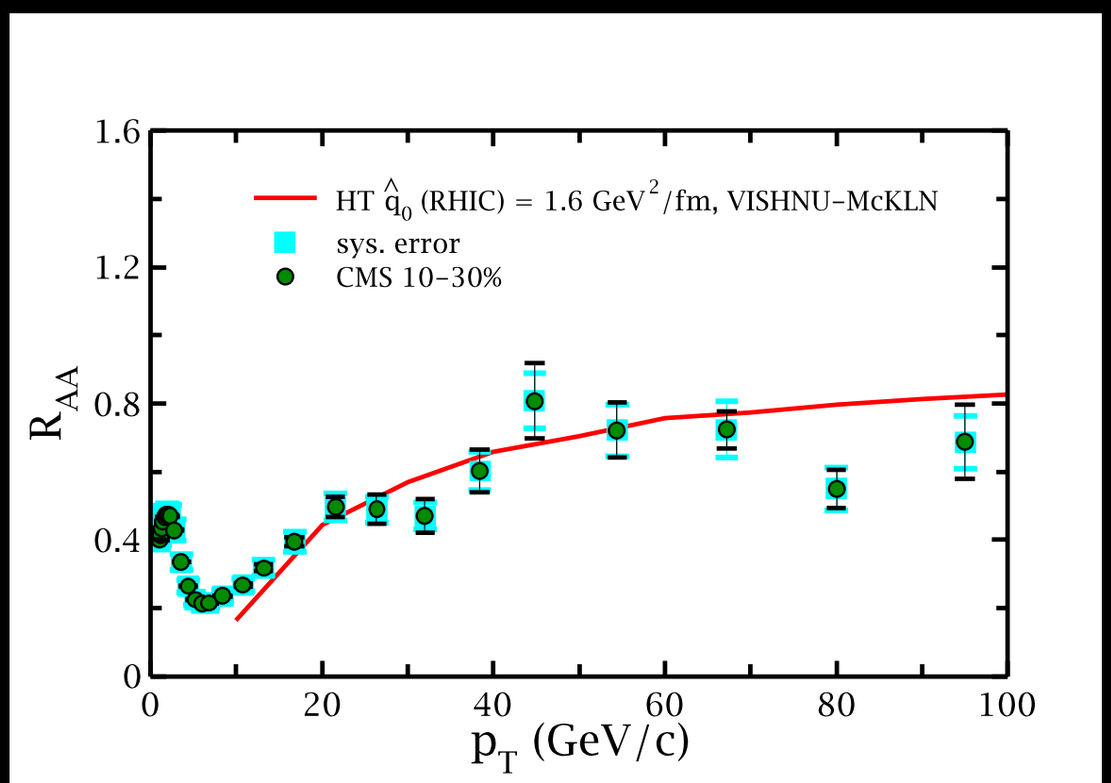
$\hat{q}(q^+, q^-)$ $\qquad$ $2q^-q^+ = Q^2,\ \frac{k_\perp^2}{2q^-} = xP^+$

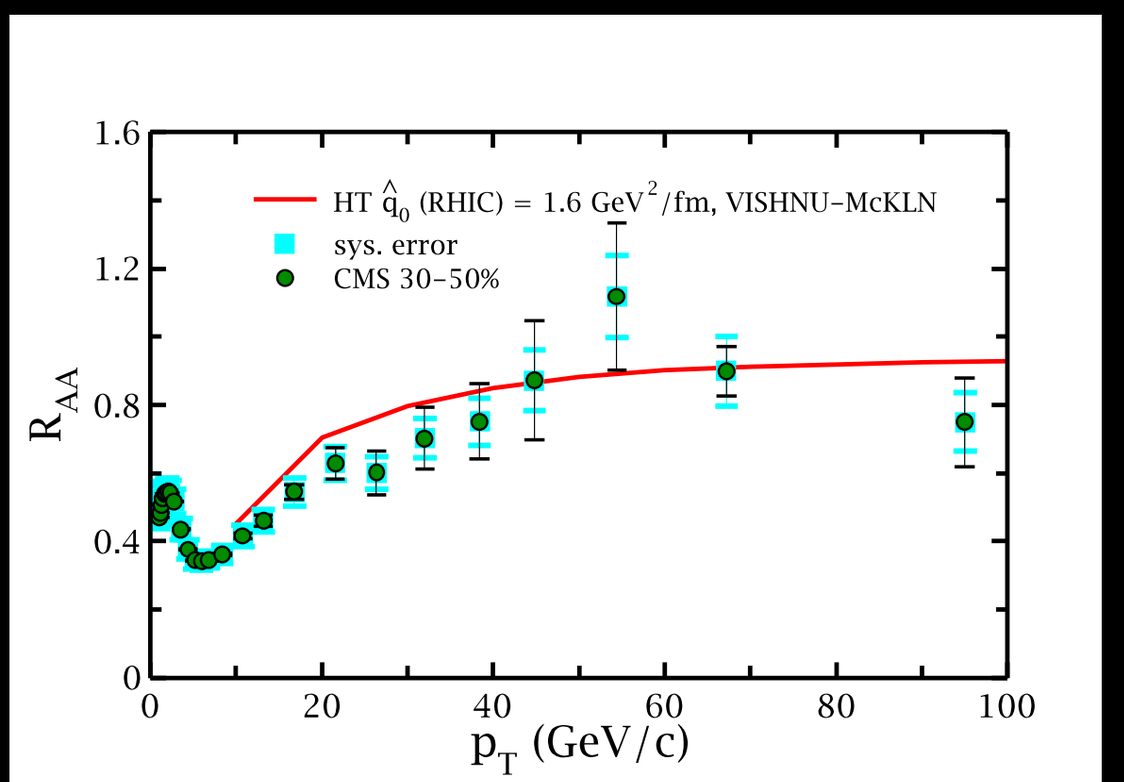
$\hat{q}$ depends on the energy and virtuality of the hard parton!

Assuming $\hat{q} \sim E^{1/2}$

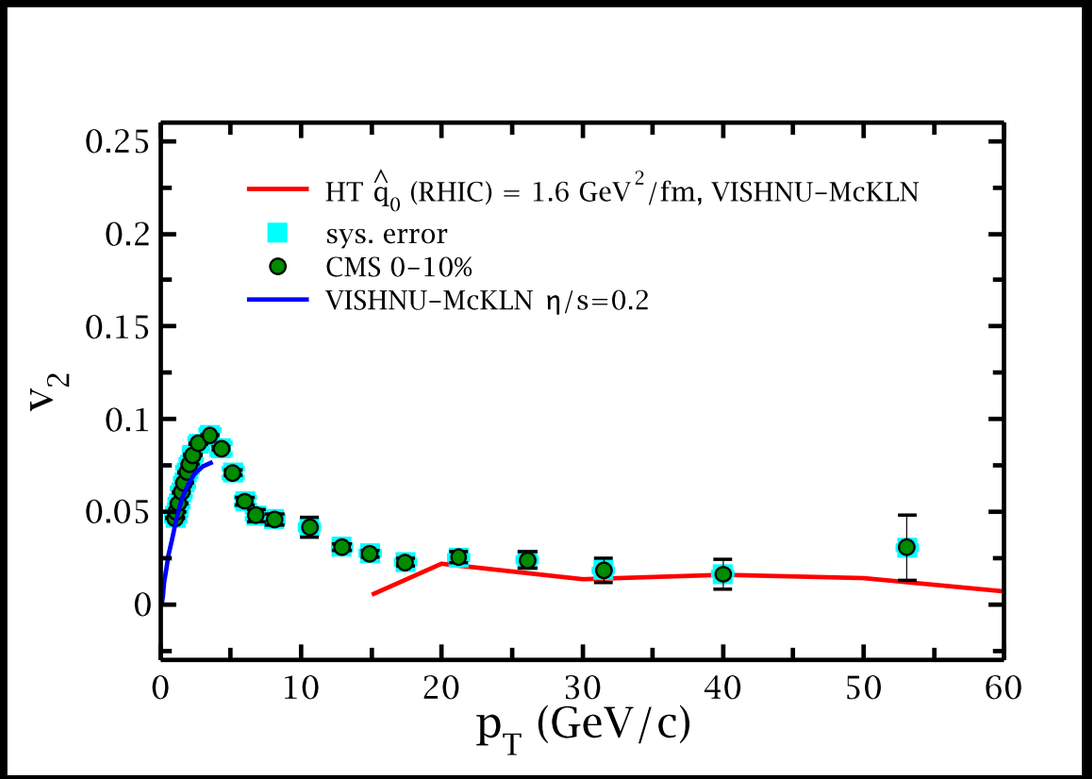


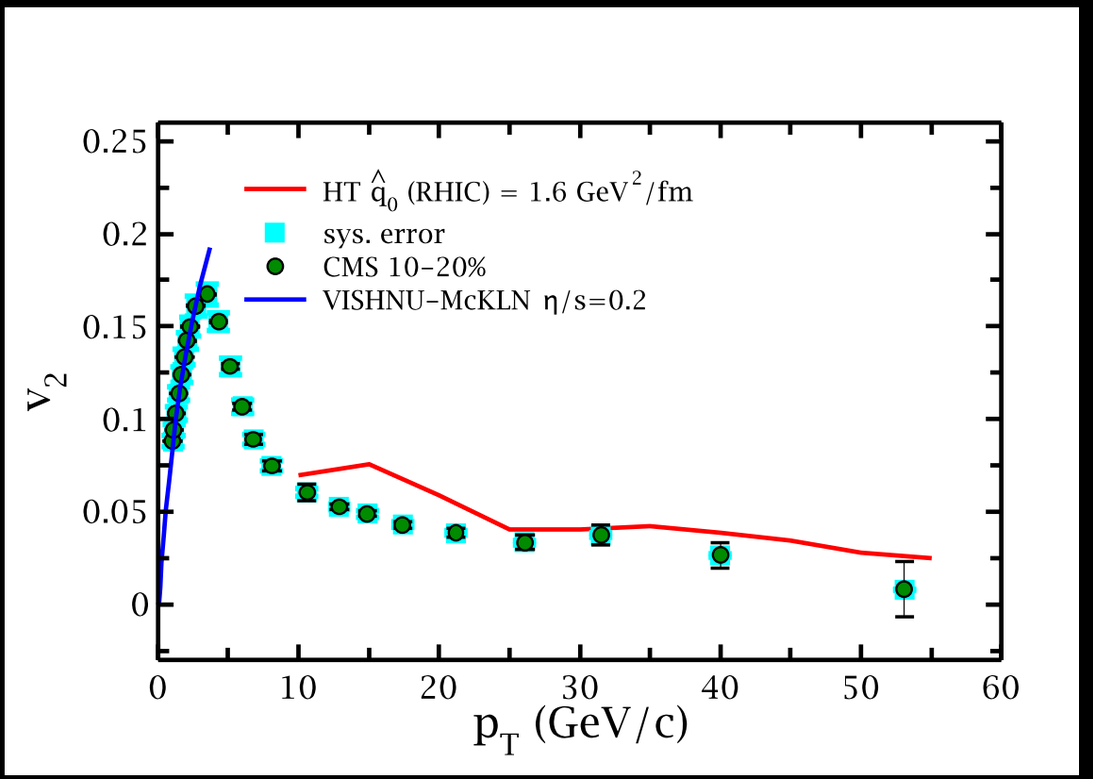


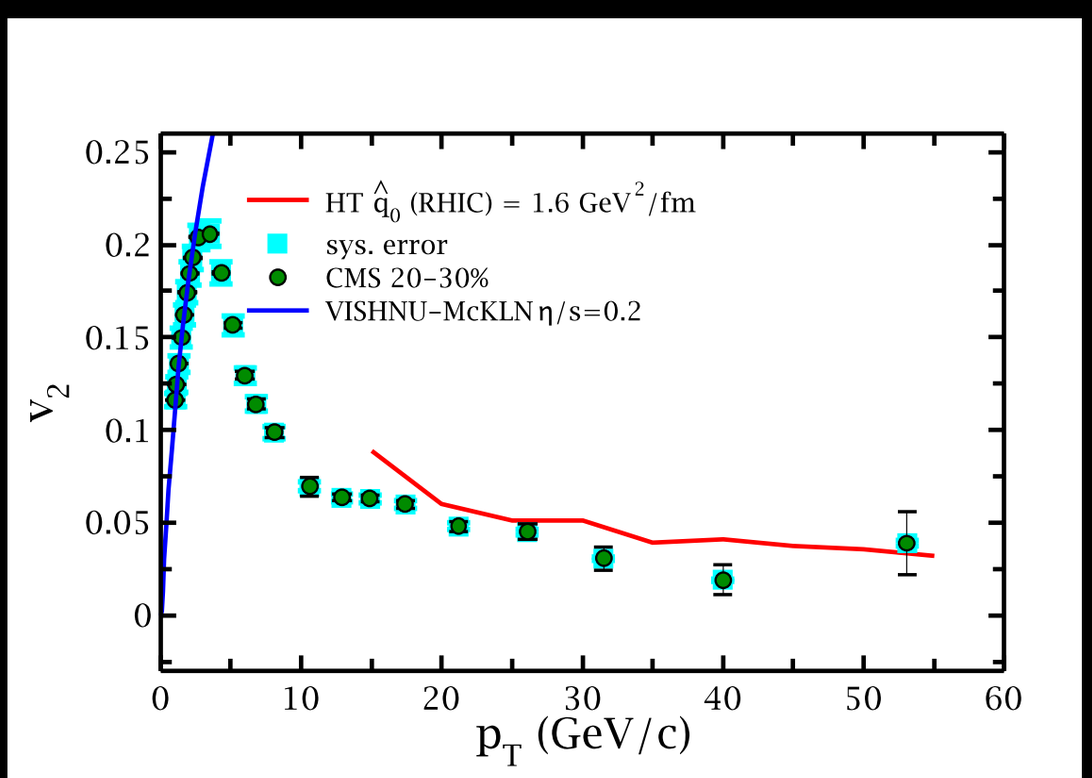


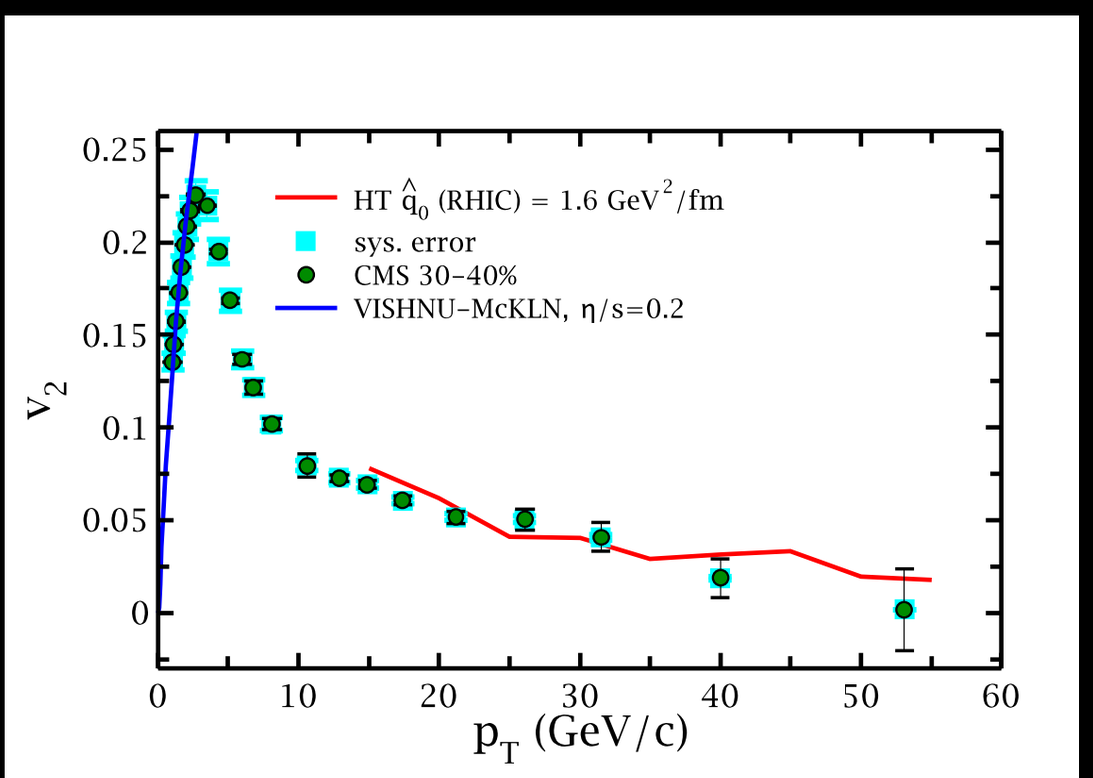


v_2 at LHC without a bump in $\hat{q}/T^3$

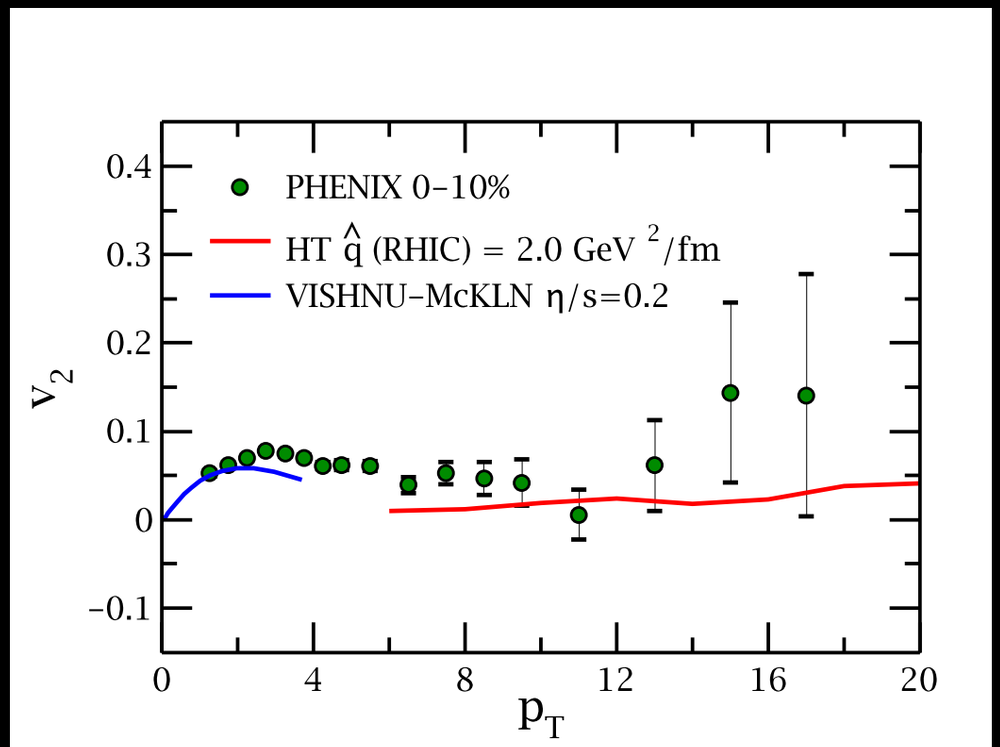


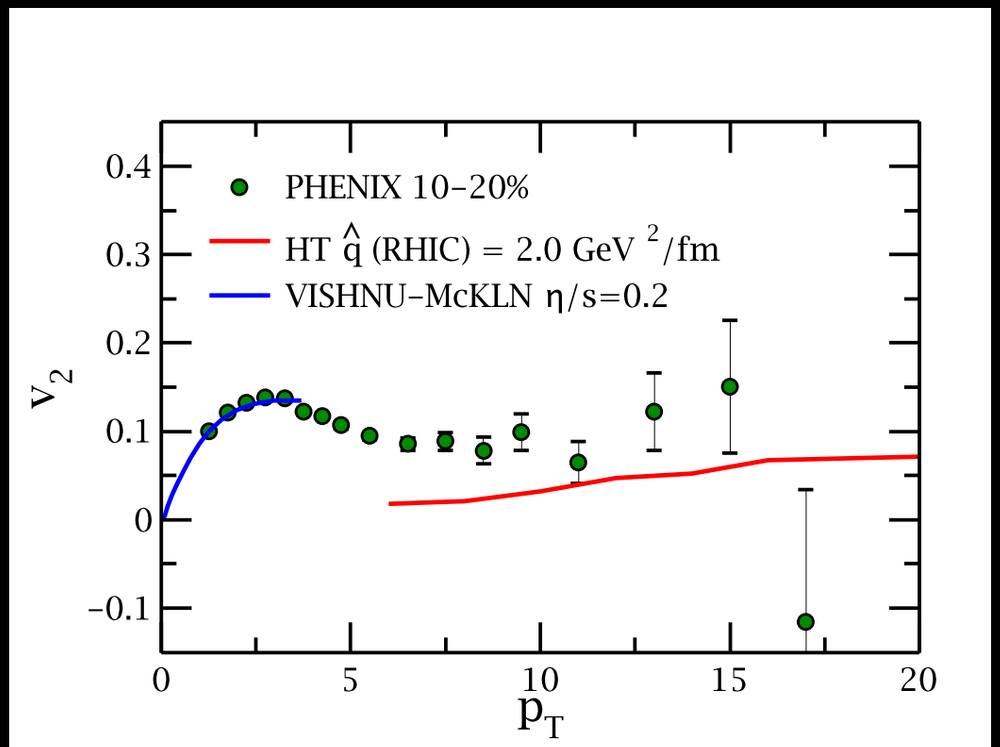


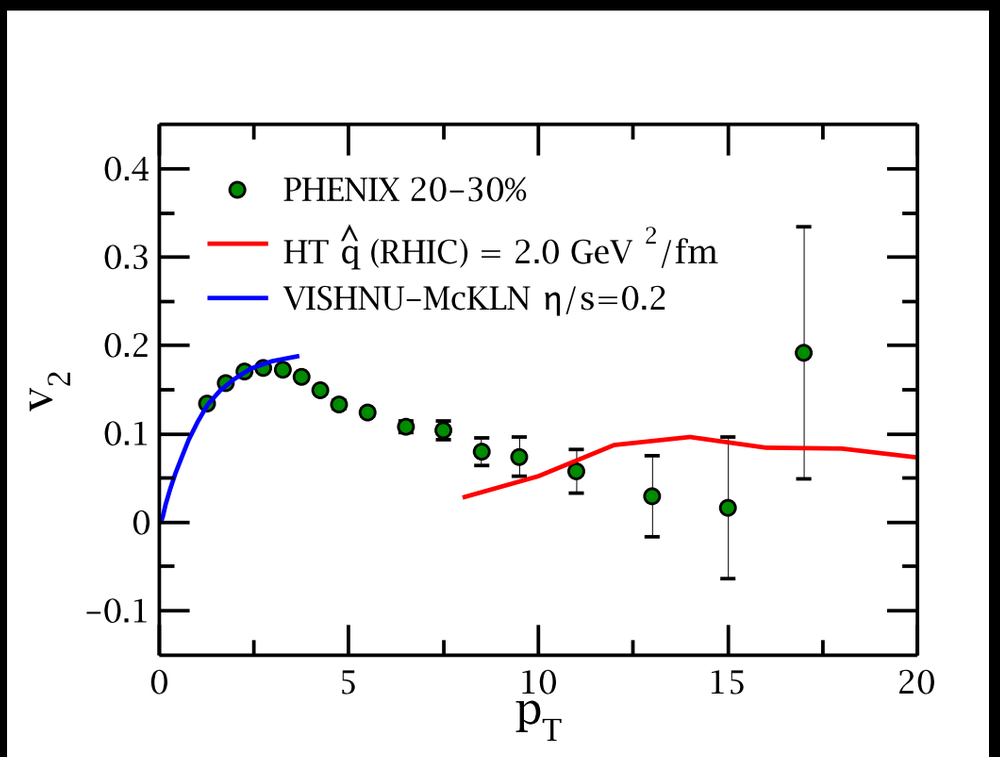


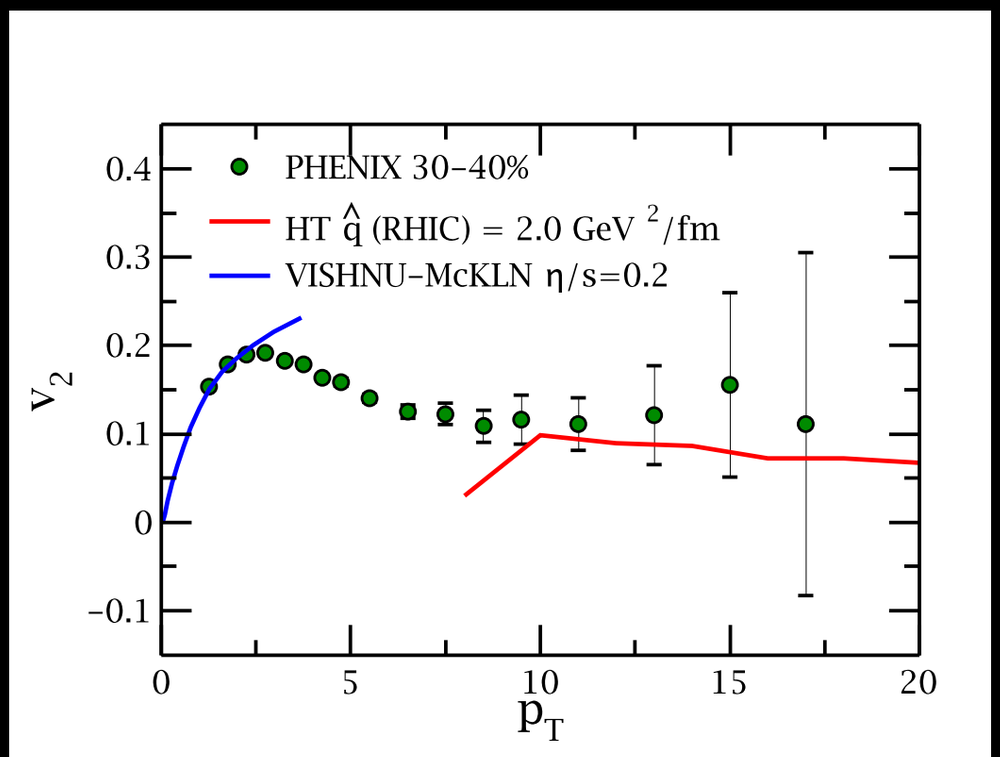


v_2 at RHIC without a bump in $\hat{q}/T^3$

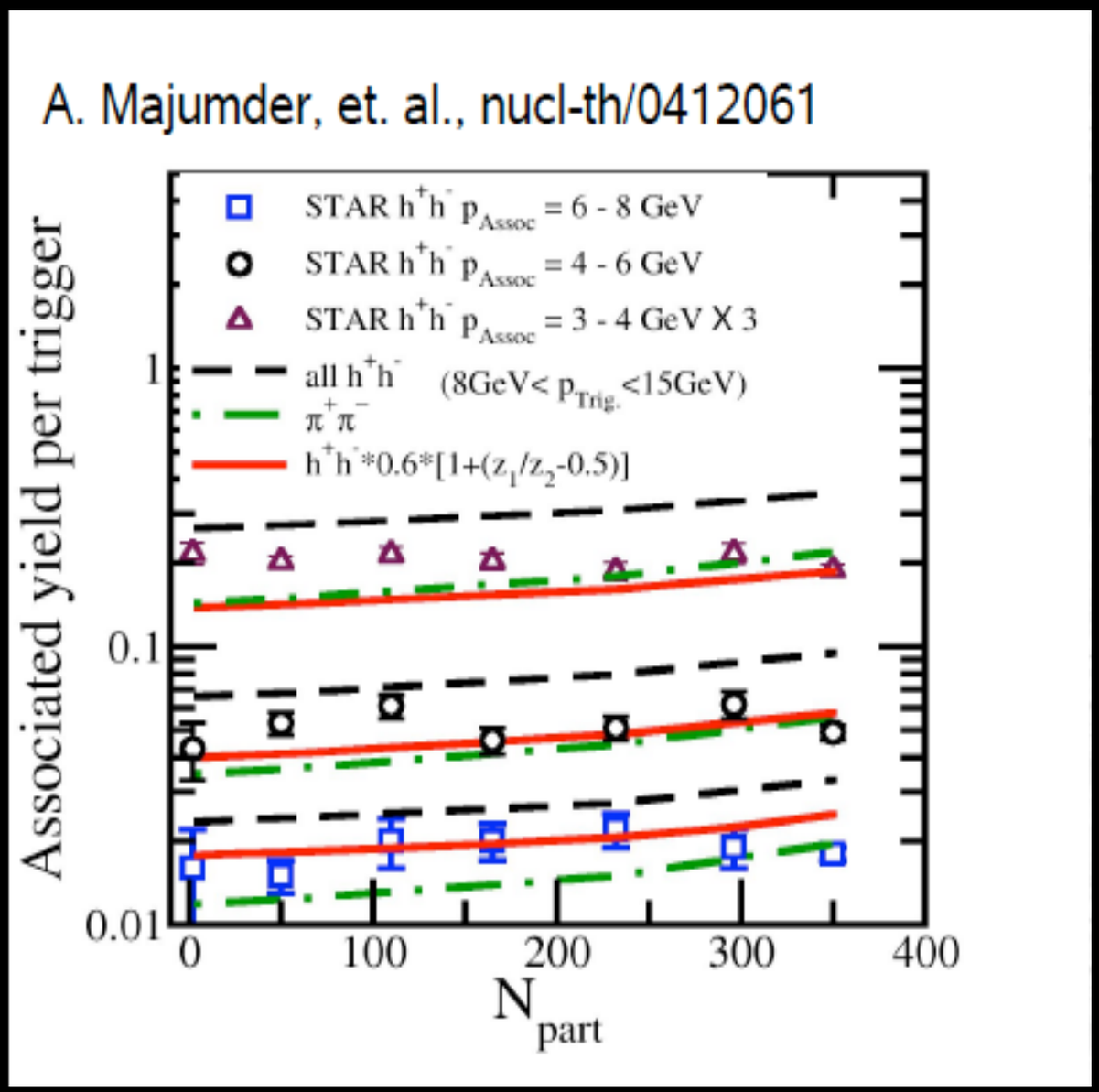


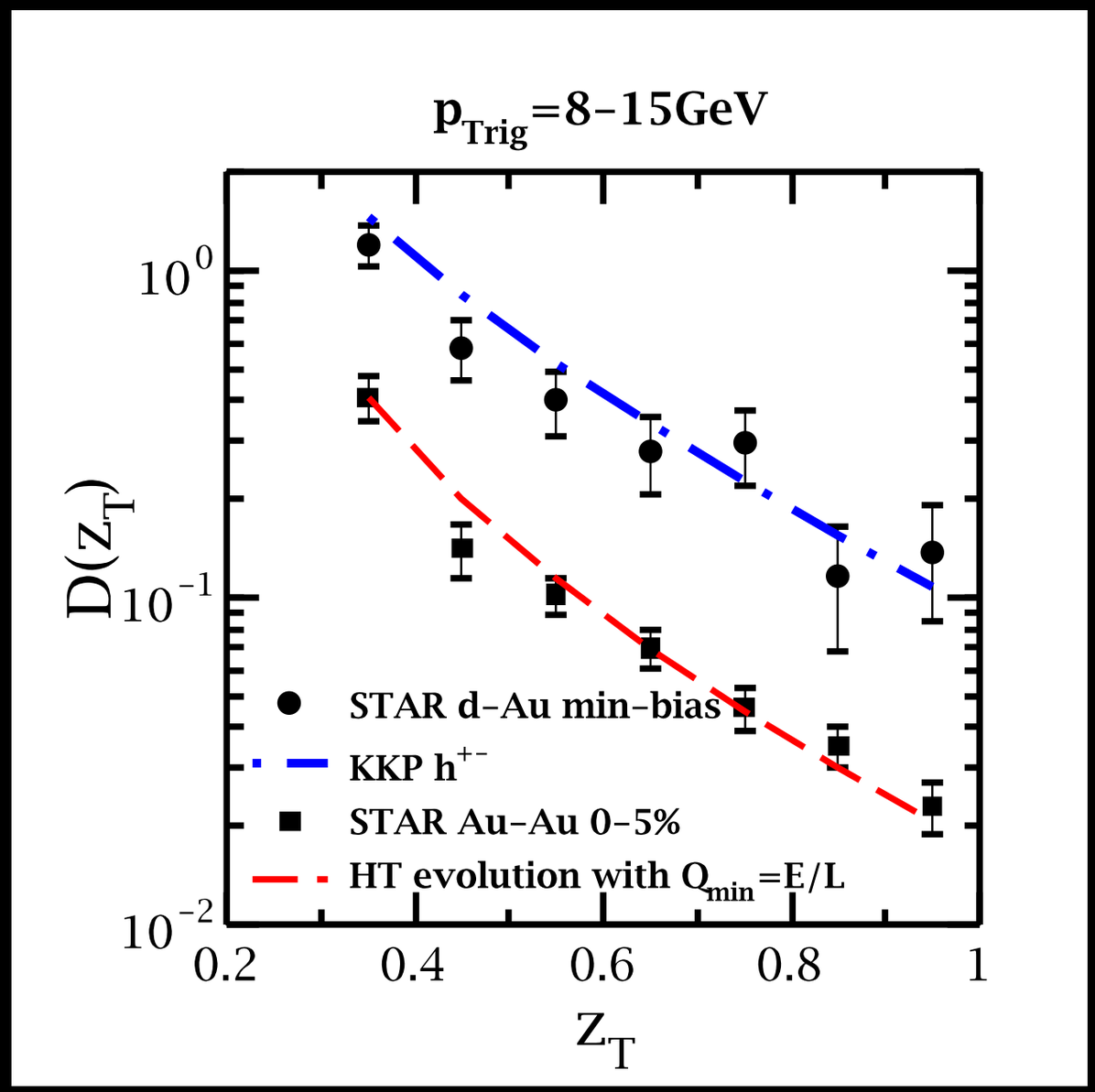






Near side and away side correlations





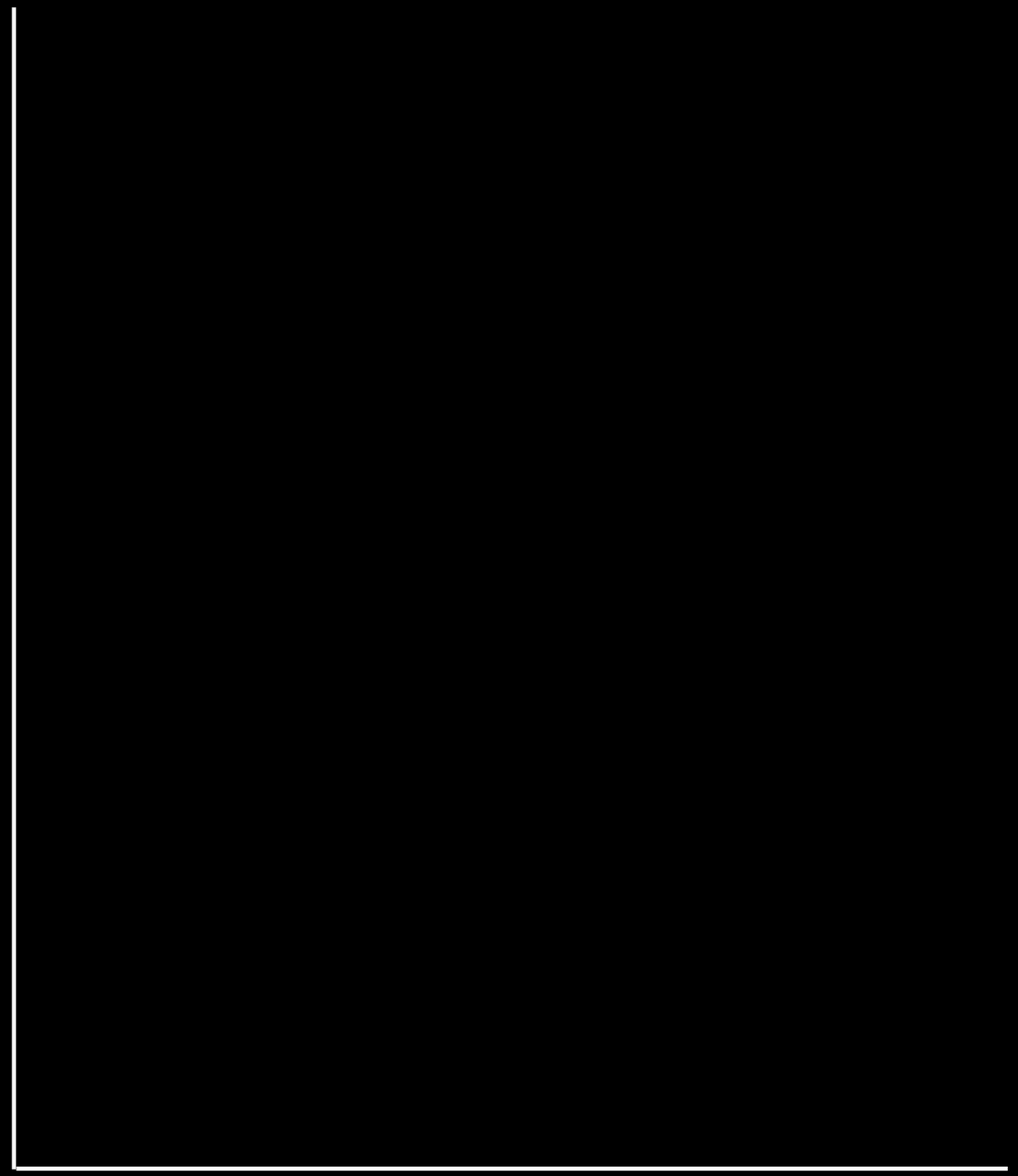
A wide range of single particle observables can be explained by a weak coupling formalism

What is missing in these calculations?

If you have x dependence

You will have non-trivial Q dependence

These will be resolved by S-PHENIX early on



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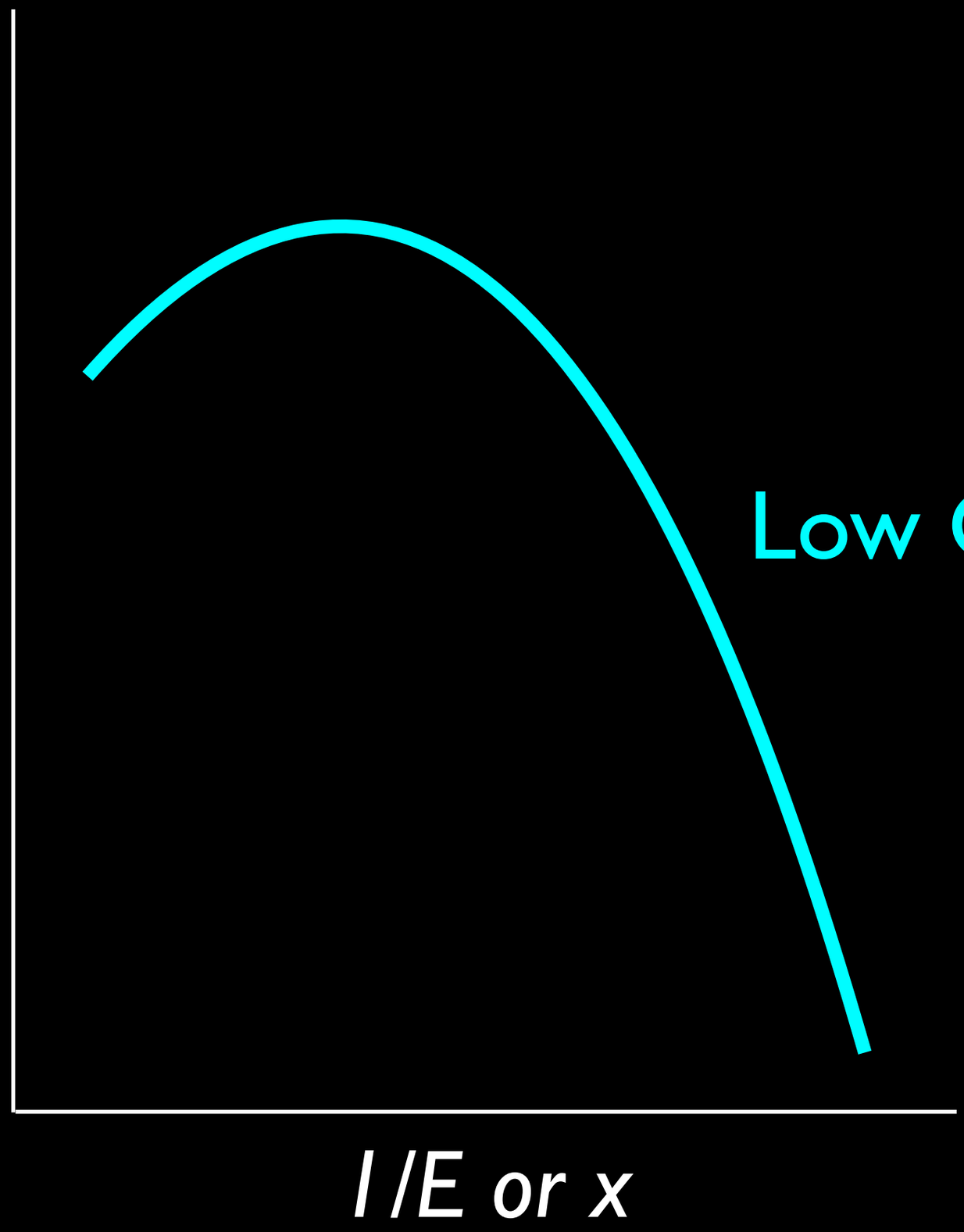

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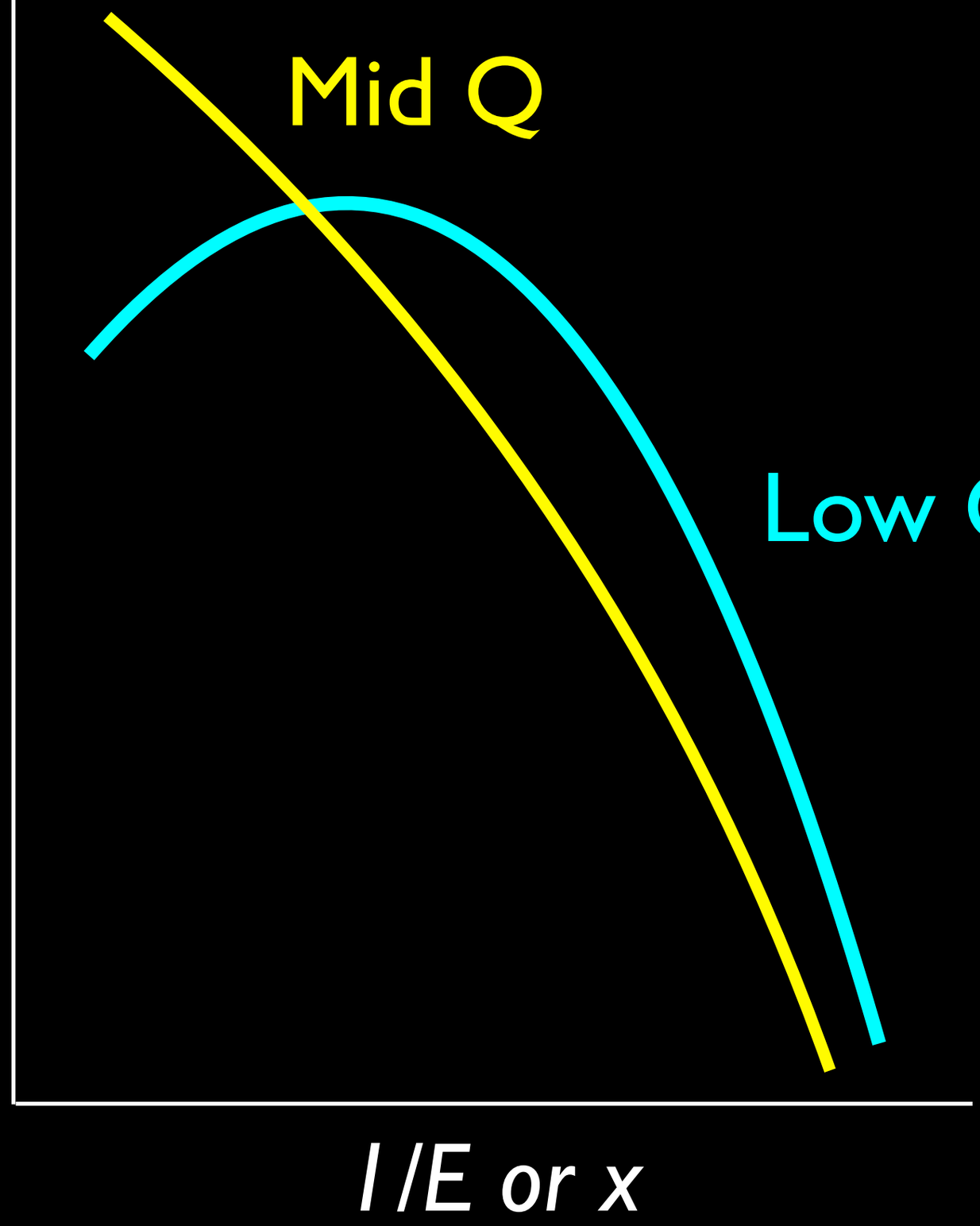

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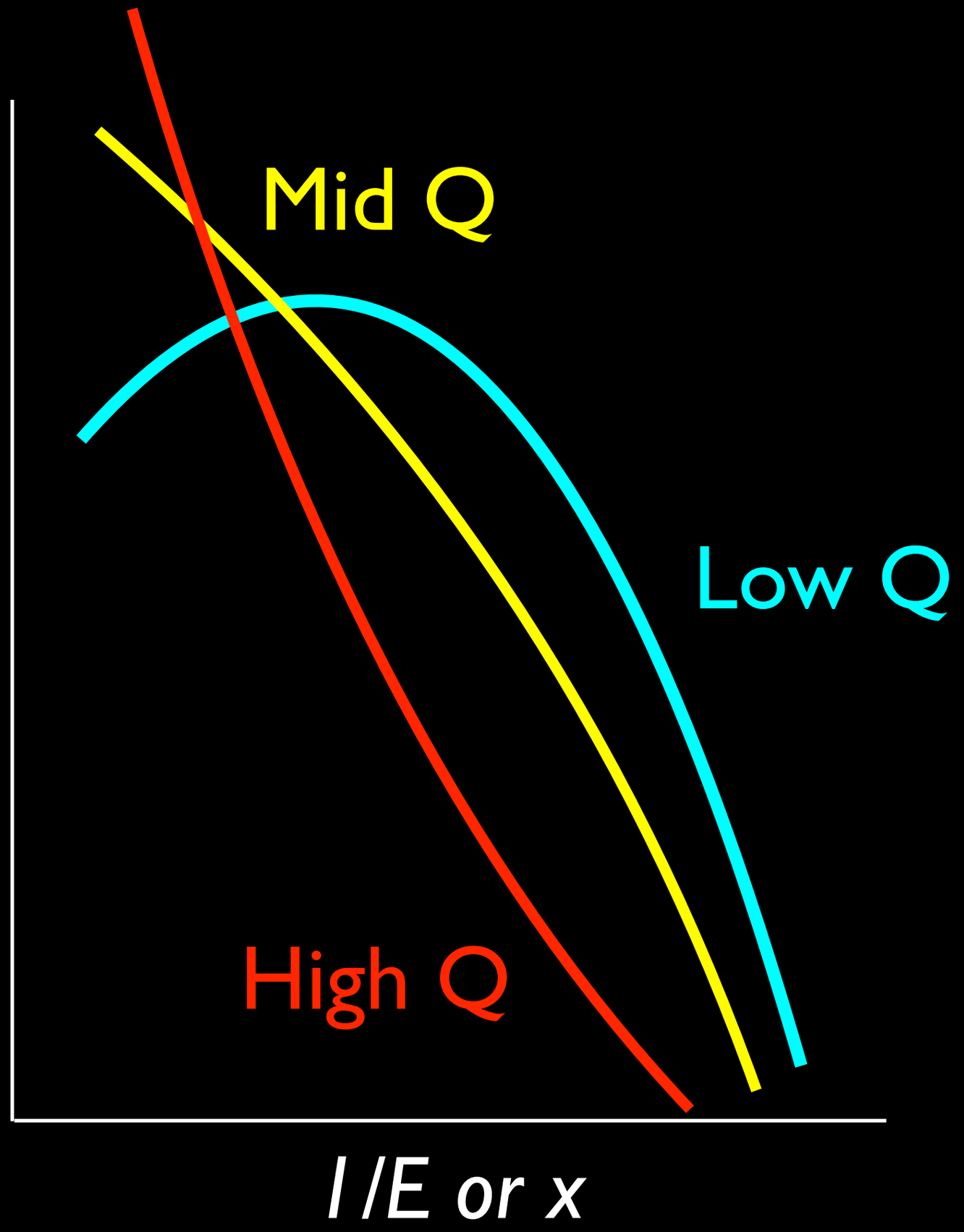


Moving from event averaged (analytic) to MCs

Note: There are several issues with MC codes
these will be resolved over the next several years

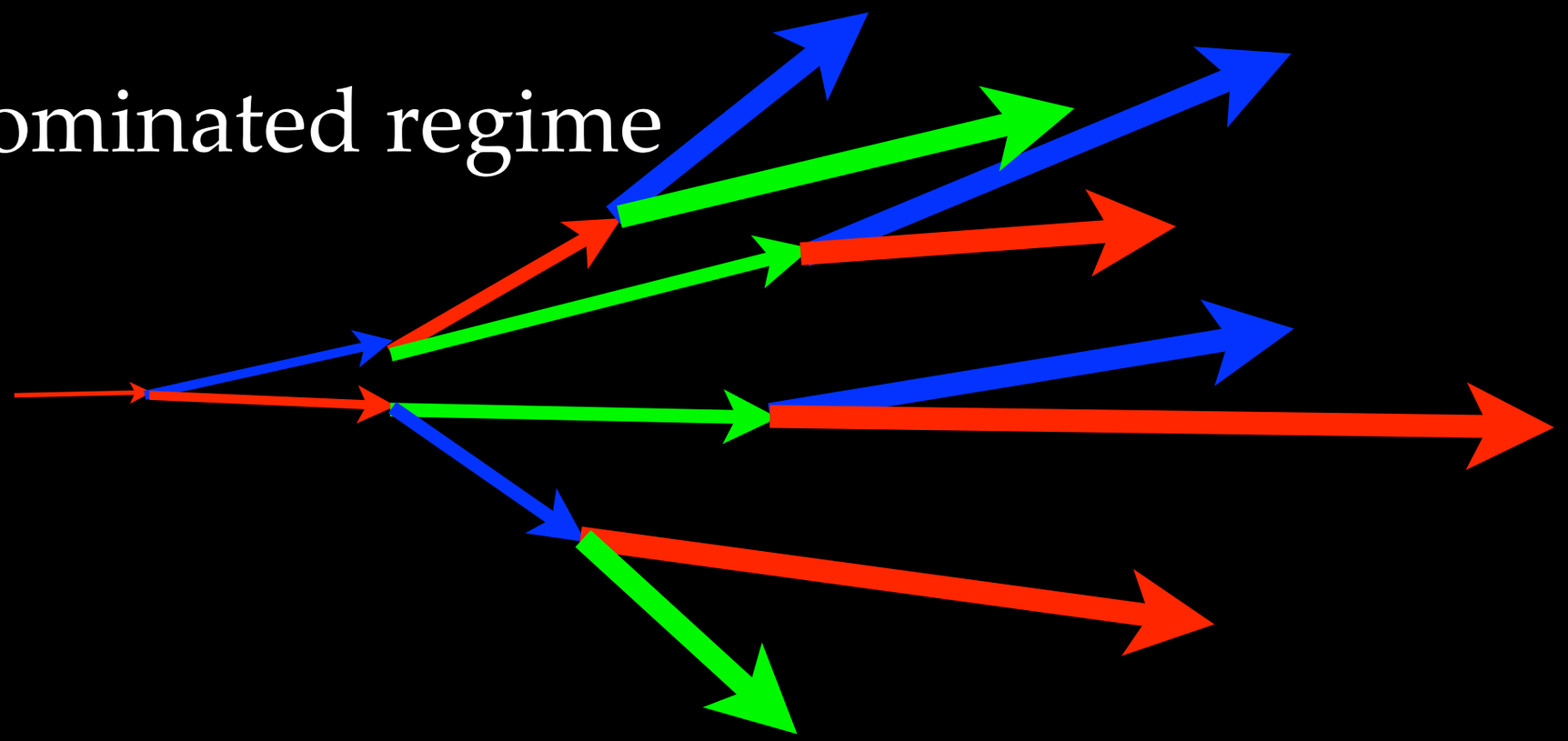
Even then there will be a role for event averaged non-simulators.

These can be used to often integrate out unknown (unwanted) physics issues

However, sophisticated MC simulators will become the tool of choice in analyzing jet data in the 2020's

High energy and high virtuality part of shower

- Radiation dominated regime



Theory: Higher Twist
MC: MATTER, LBNL-CCNU, YaJEM*

High energy and high virtuality part of shower

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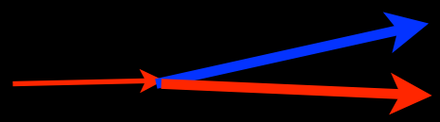

Theory: Higher Twist
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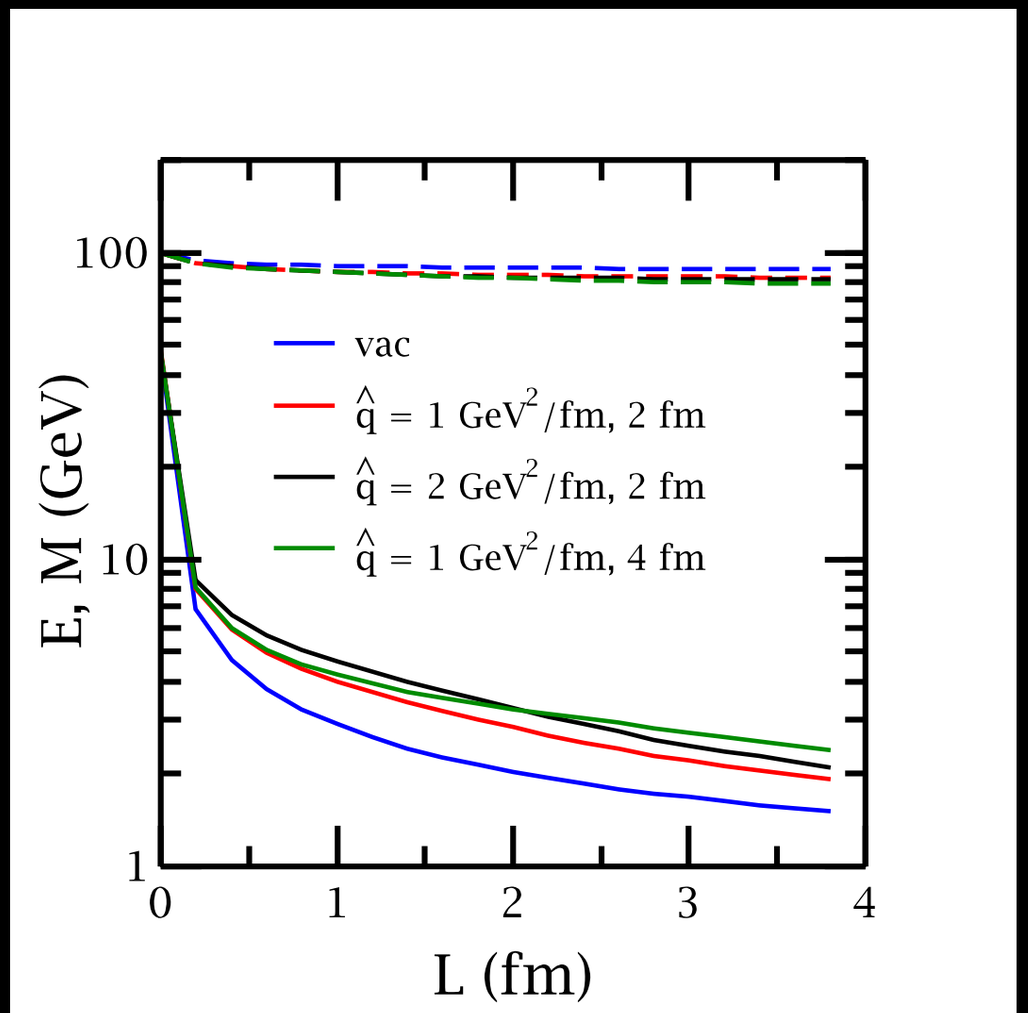

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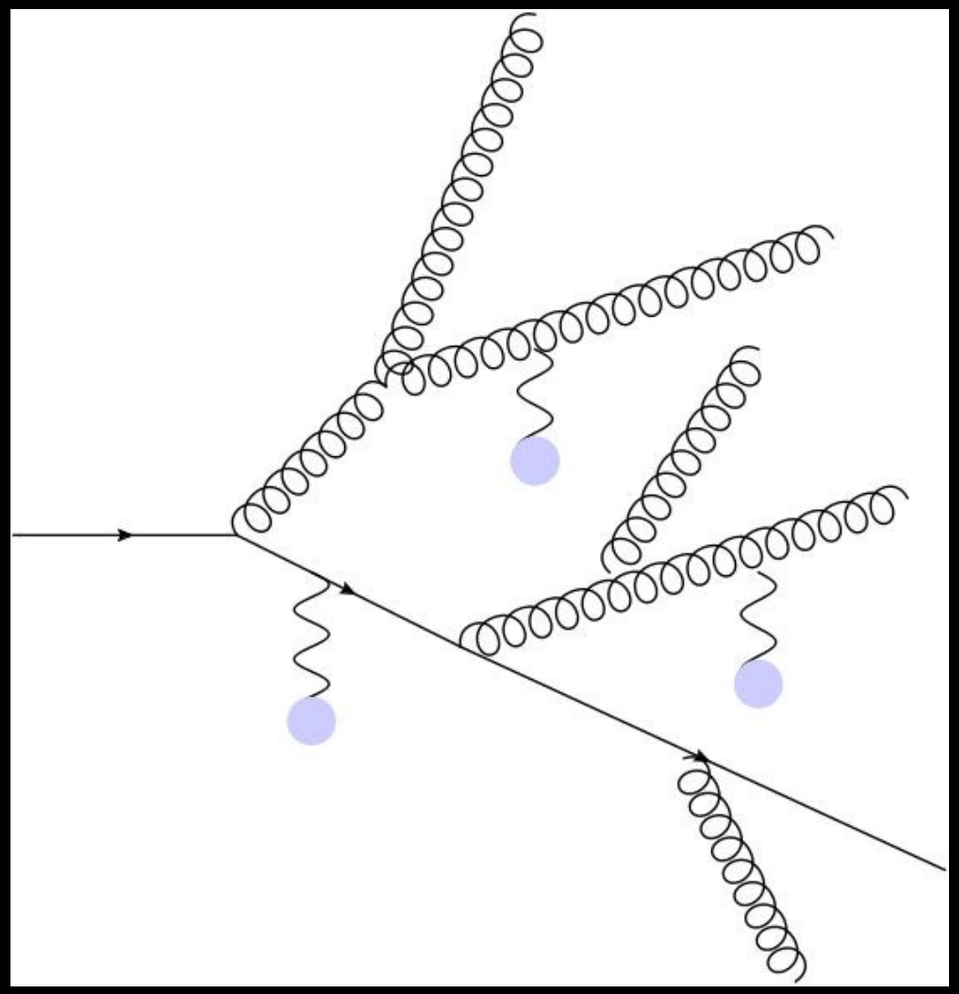

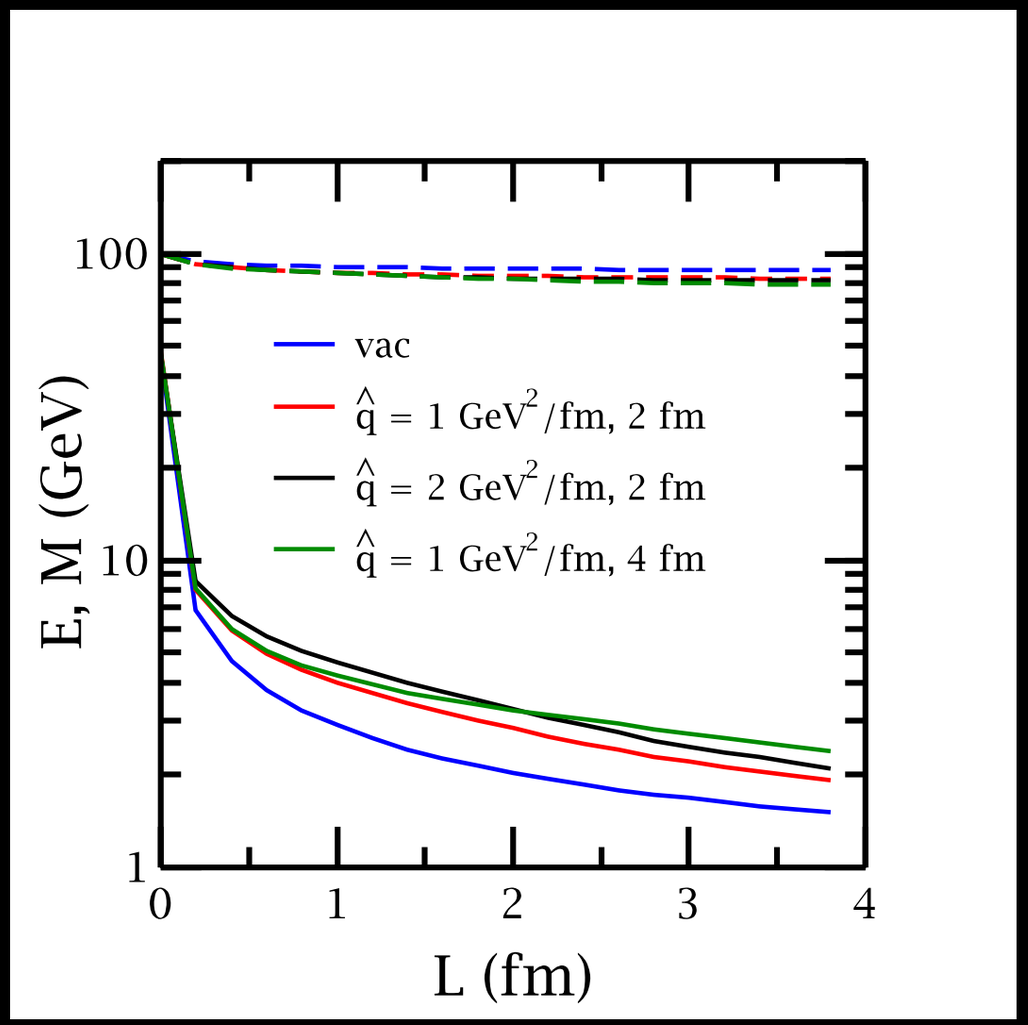

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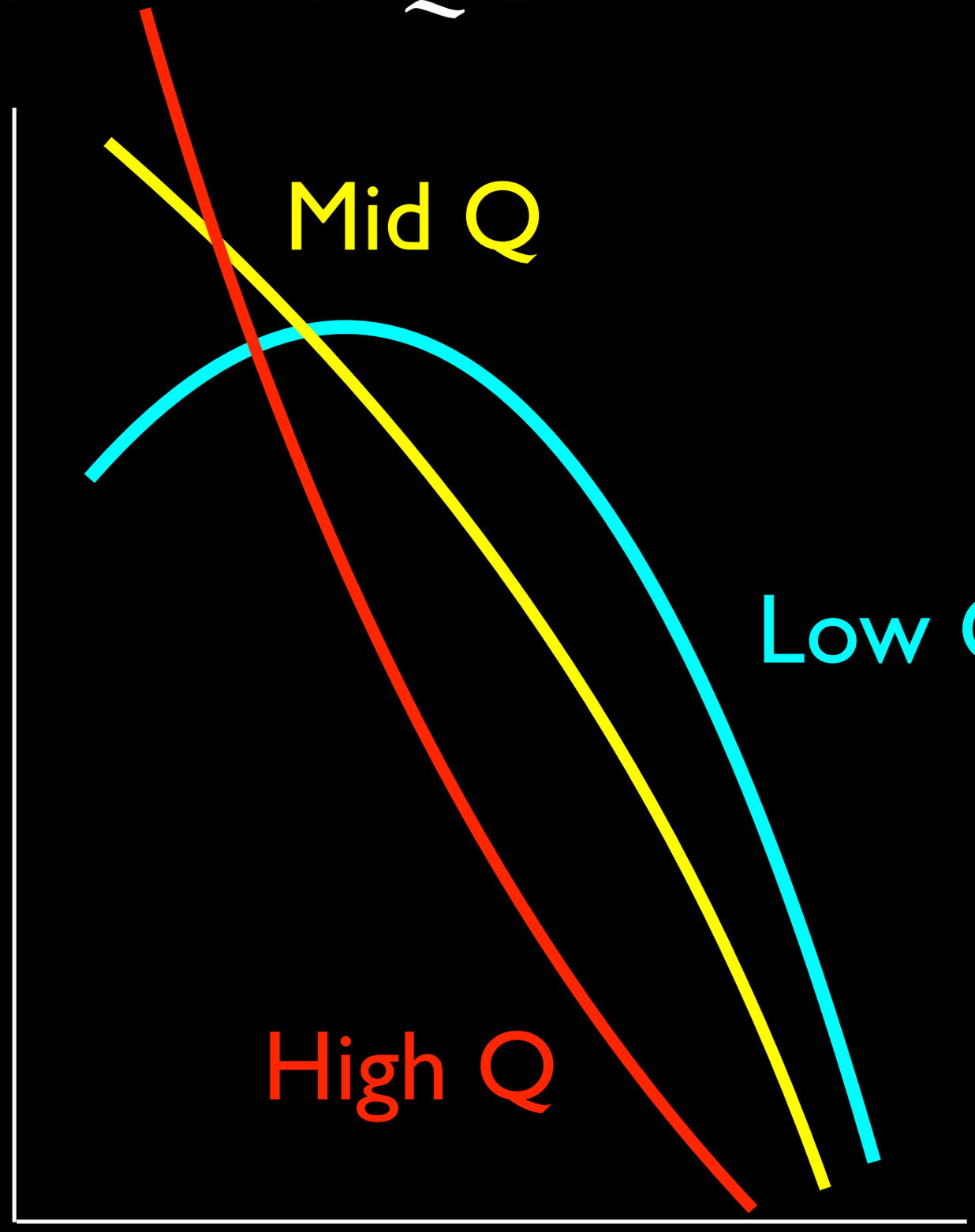
Extracting a $\hat{q}$, from the QGP-PDF

Extracted $\hat{q}$ has a lot or fluctuation included in it. Looks different at different scales



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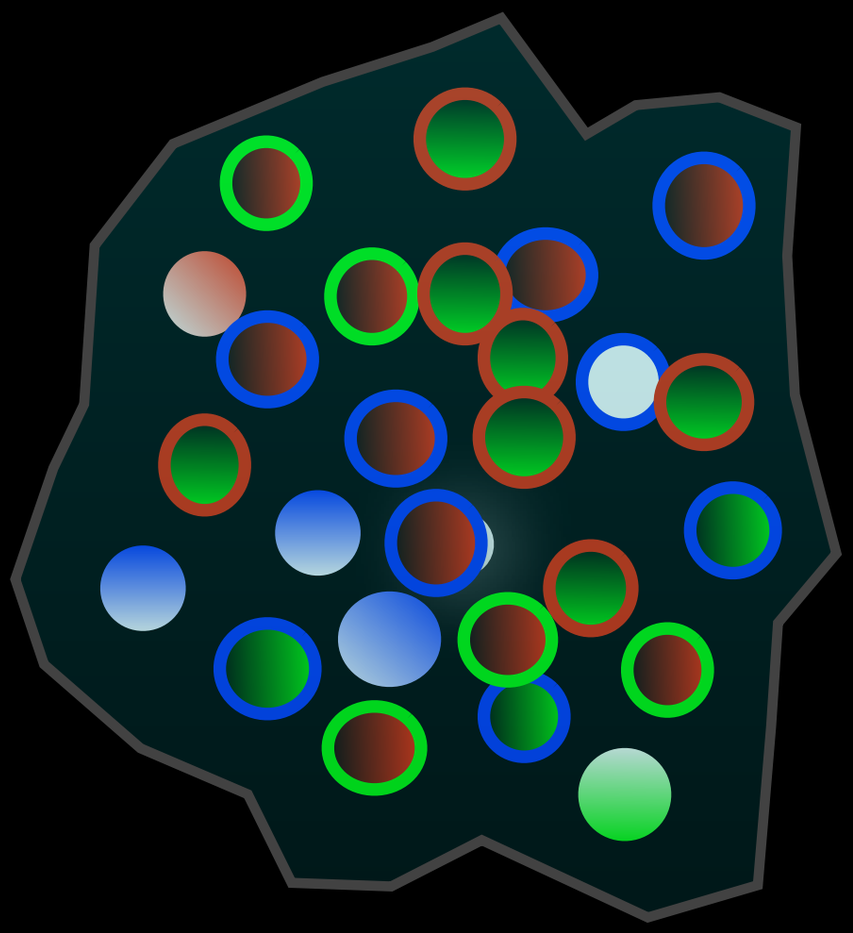
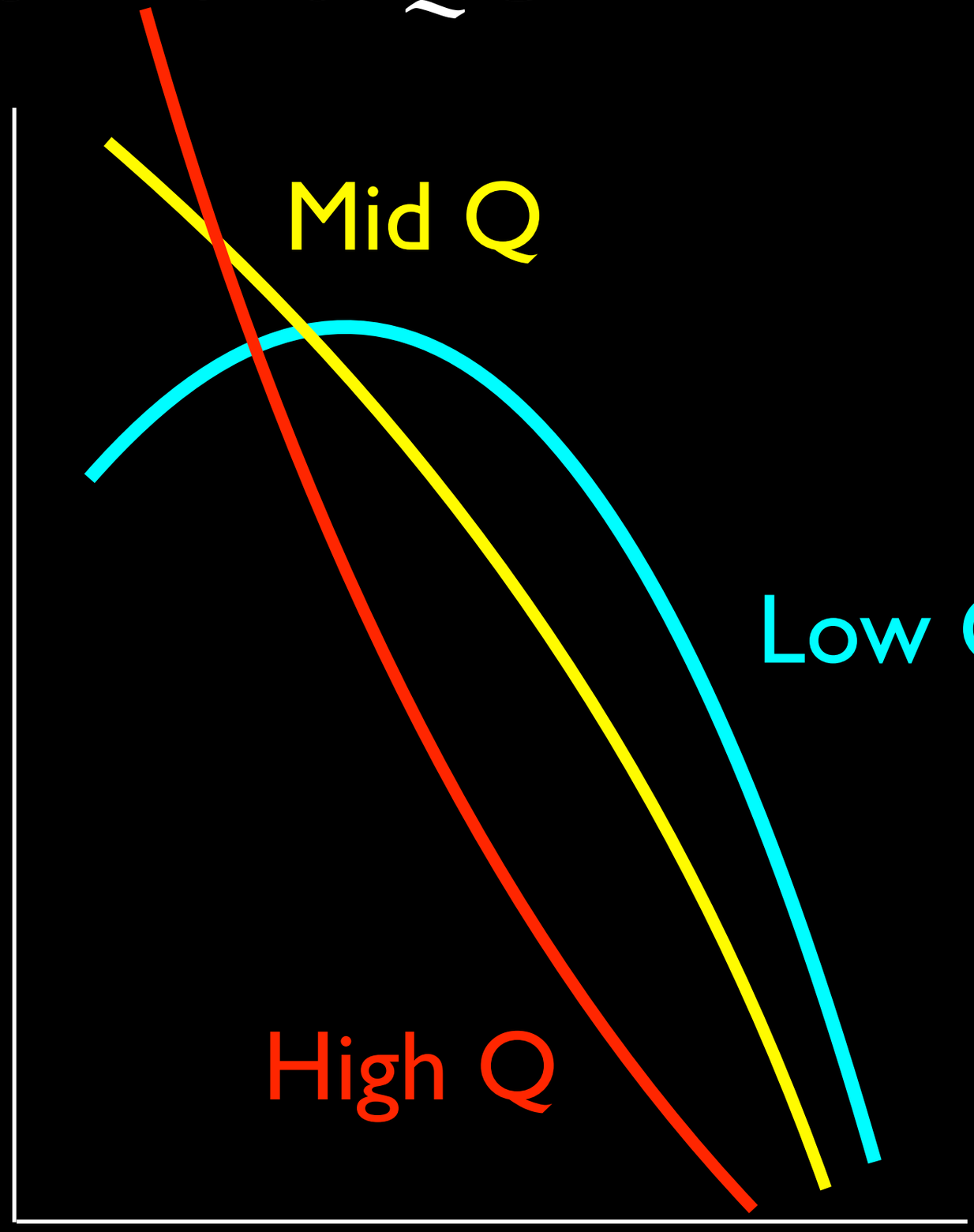
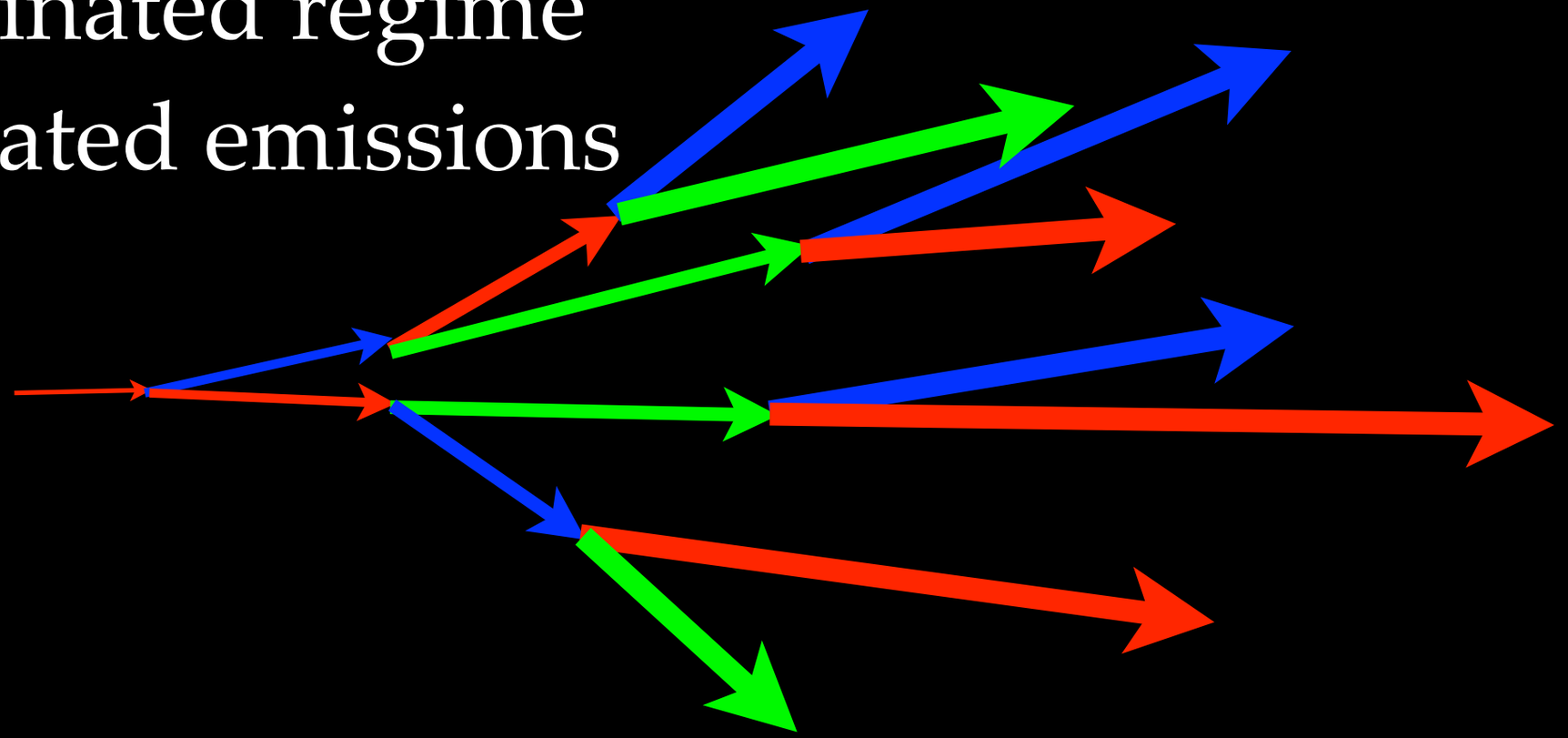




Low virtuality, high energy part

Scattering dominated regime

Few, time separated emissions



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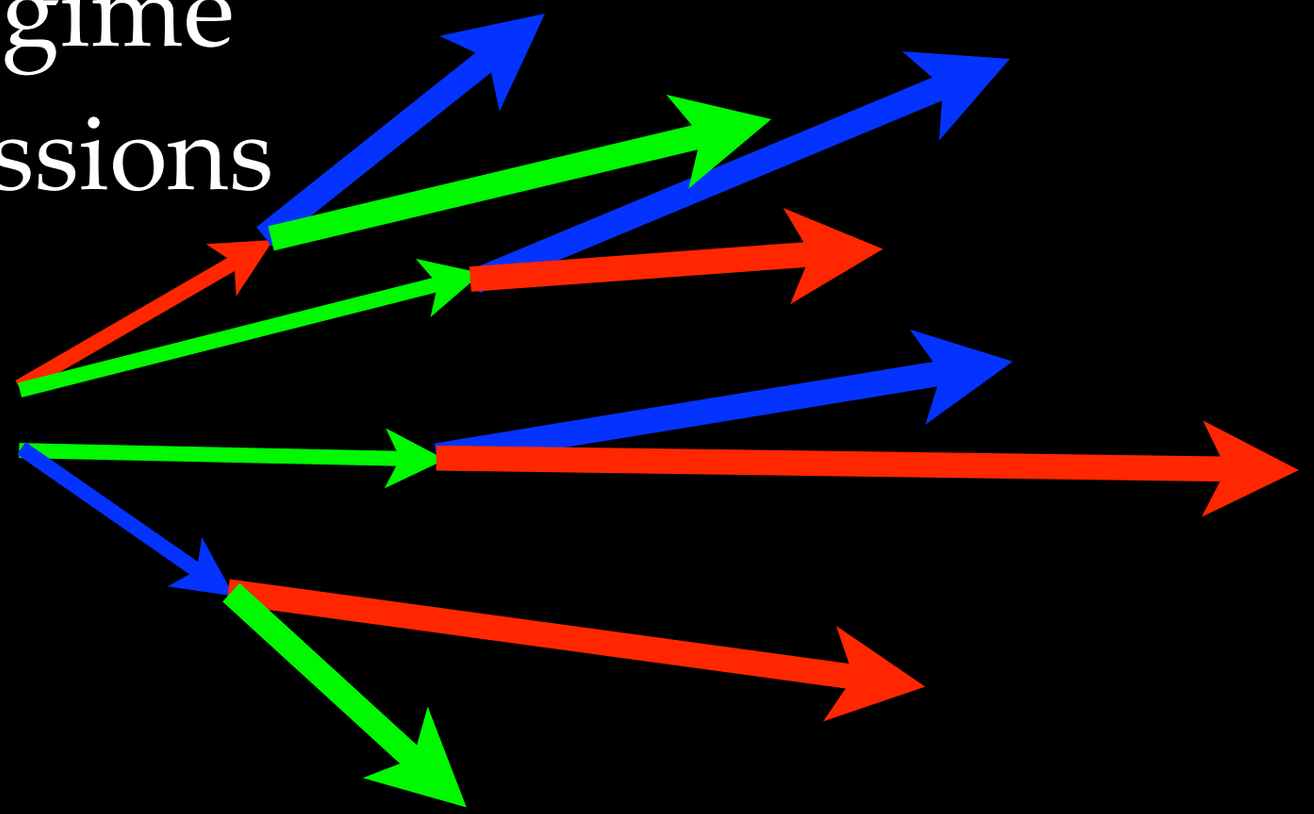

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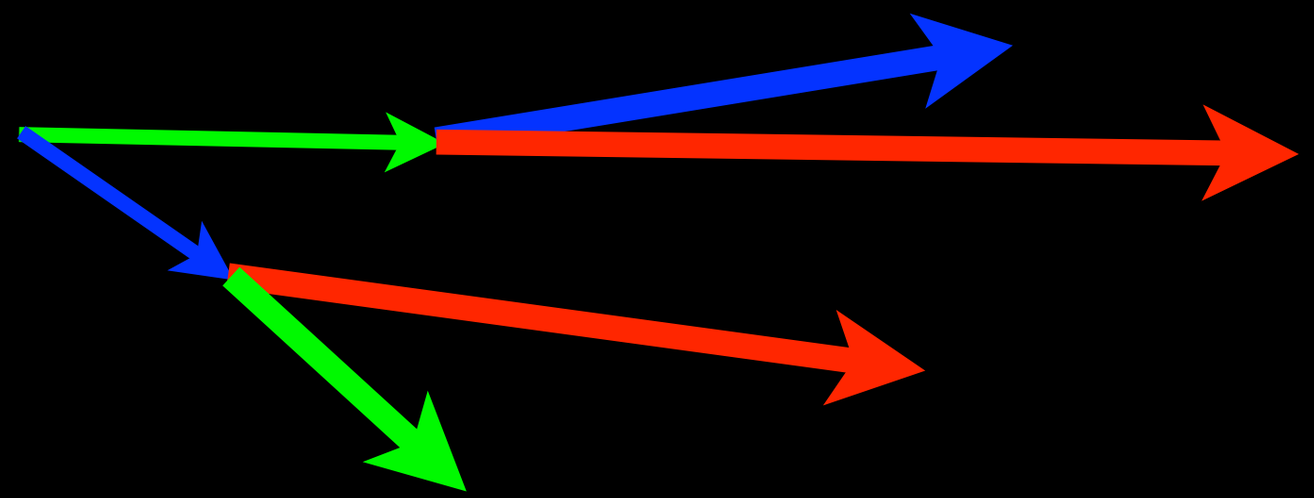

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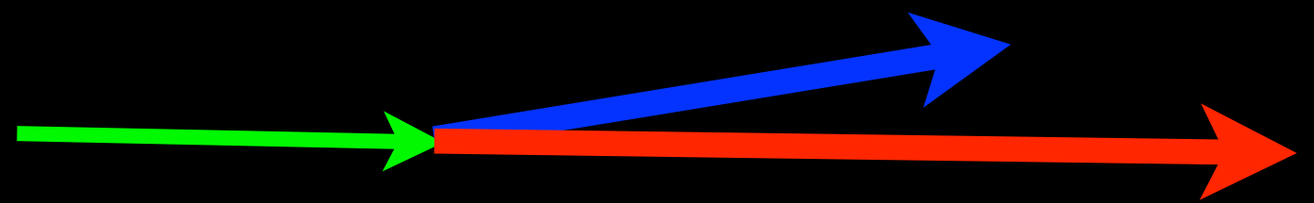

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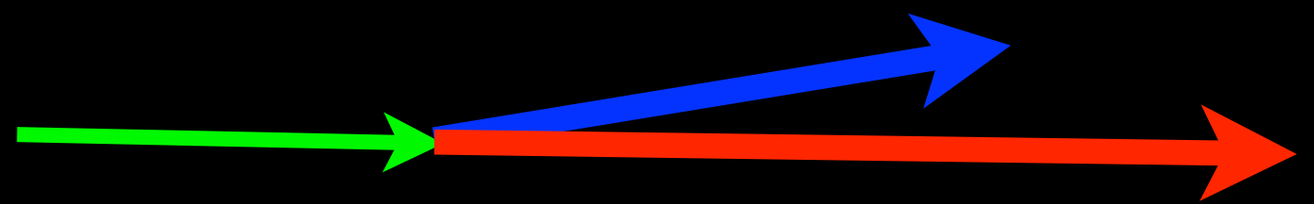

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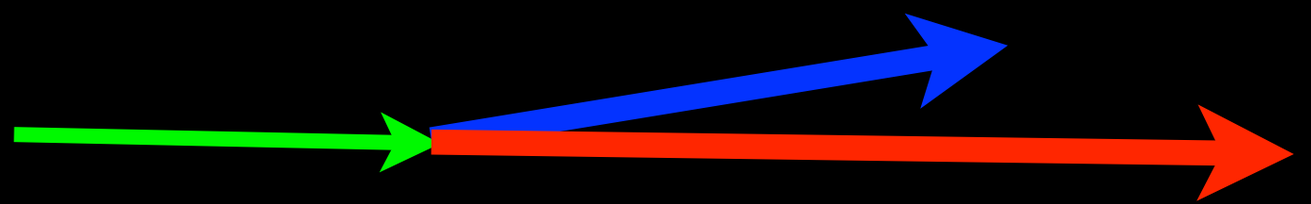

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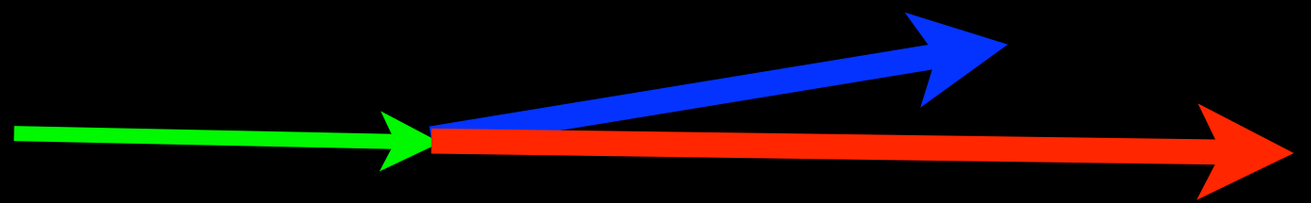

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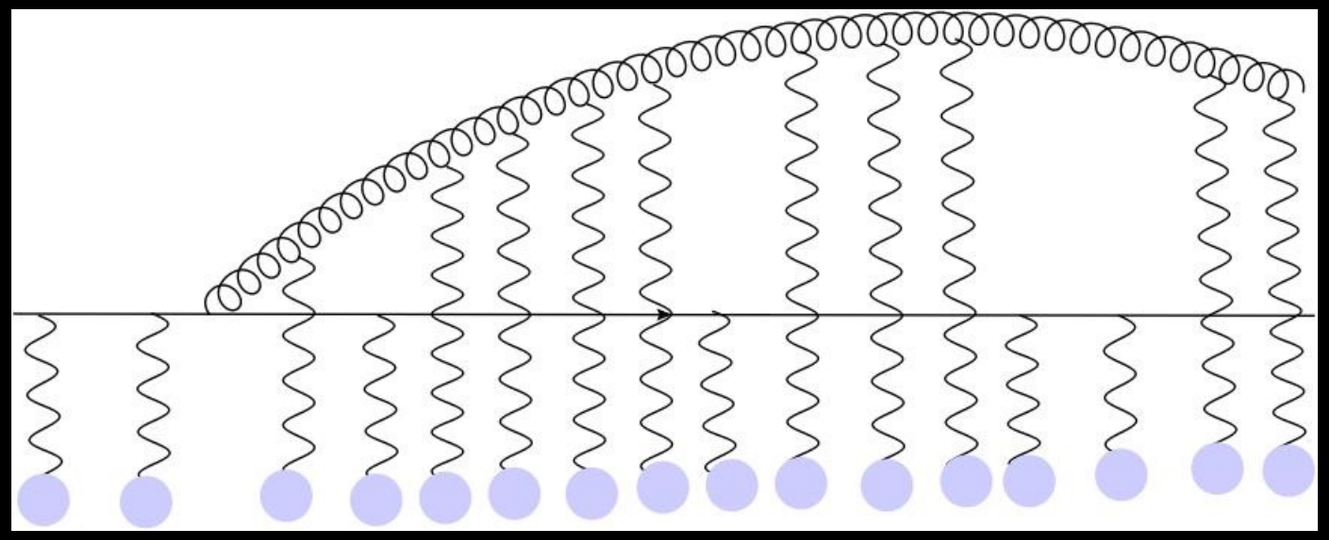

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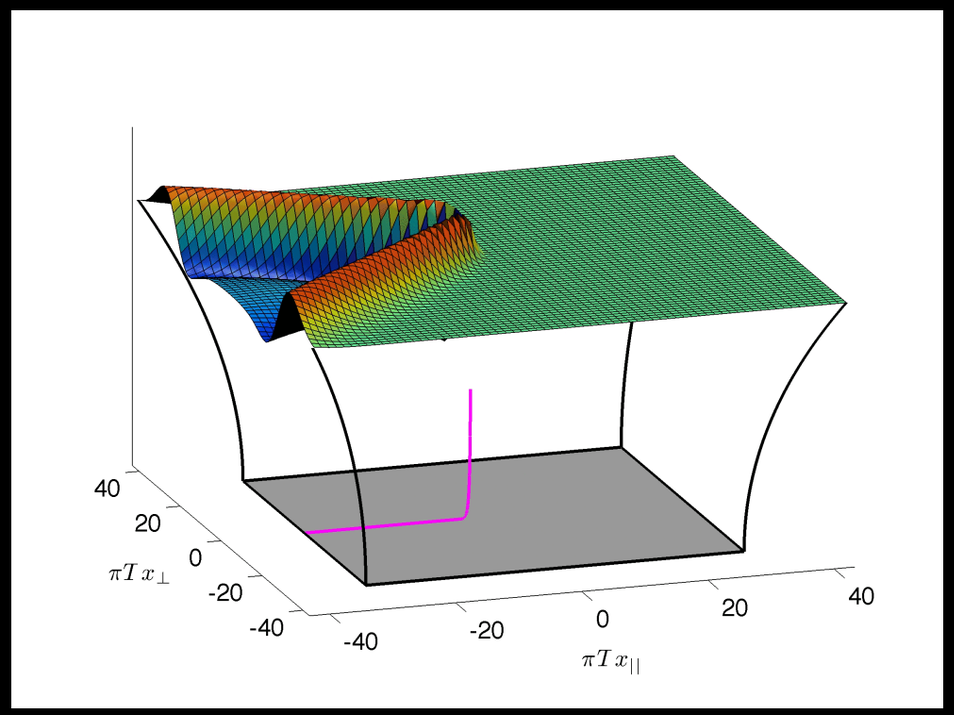

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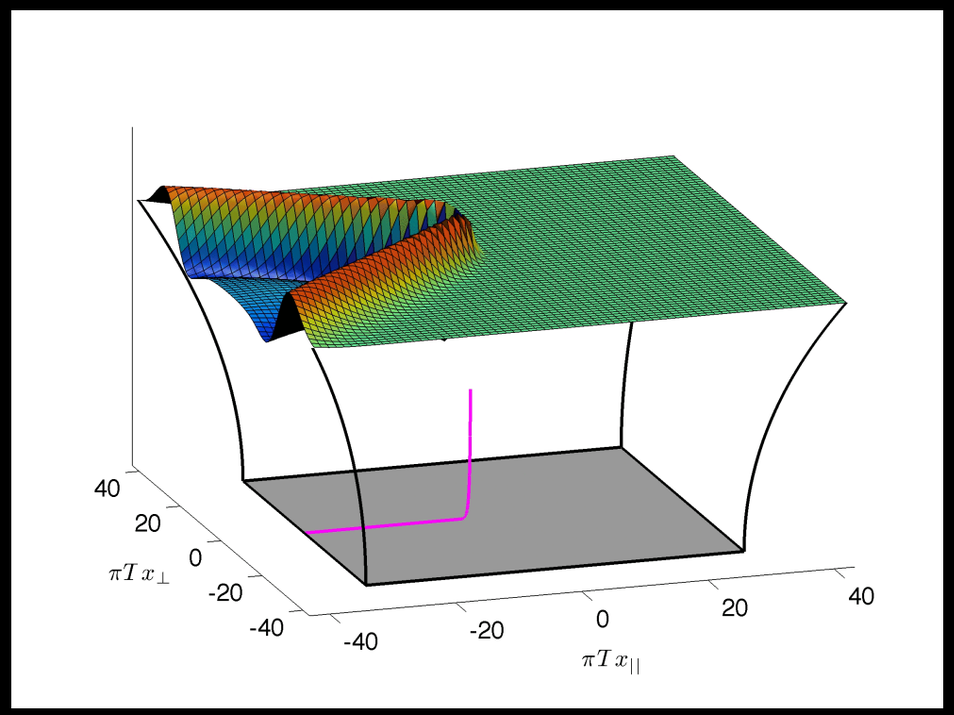
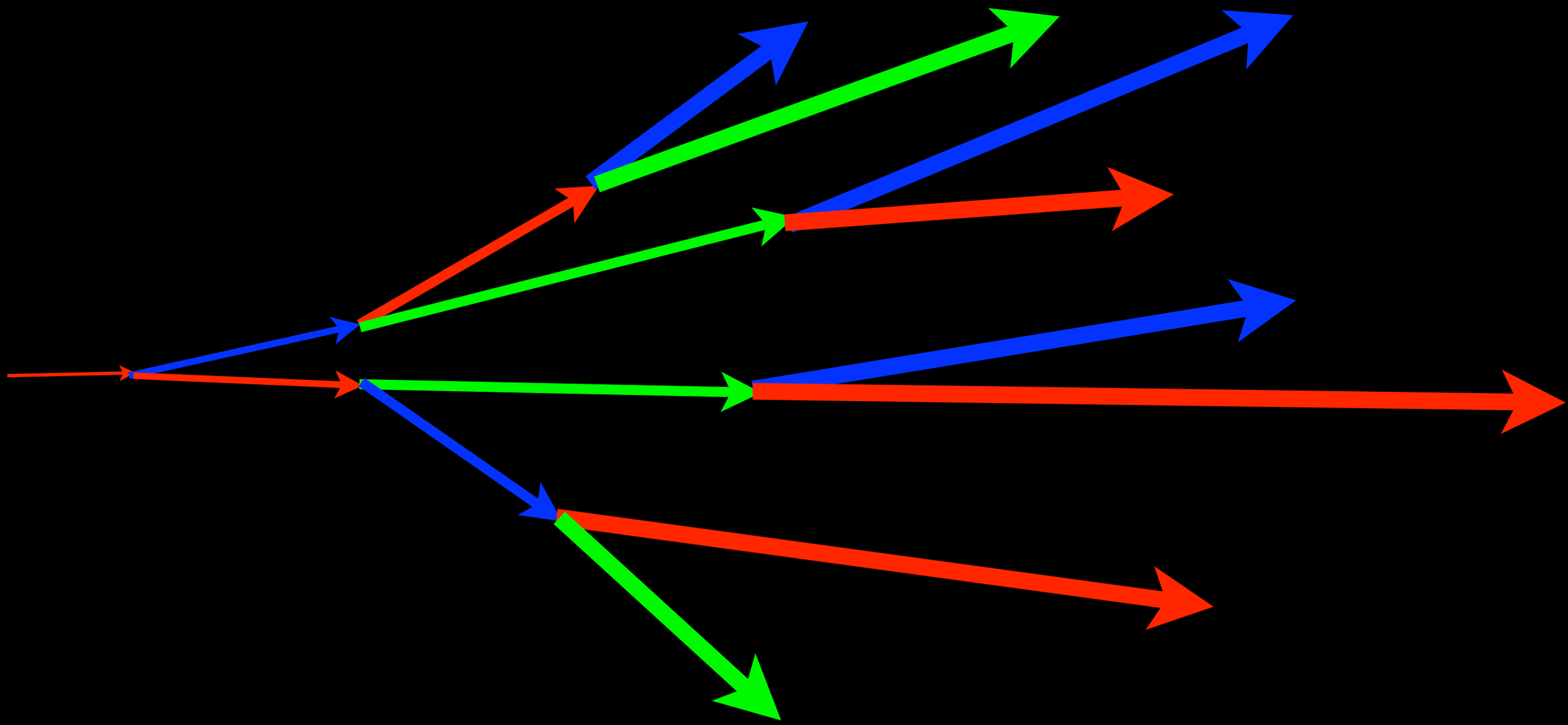


P. Chesler, W. Horowitz
J. Casalderrey-Solana, G. Milhano, D. Pablos, K. Rajagopal

Grand picture:
boundaries depend on type I coefficients



In a static brick

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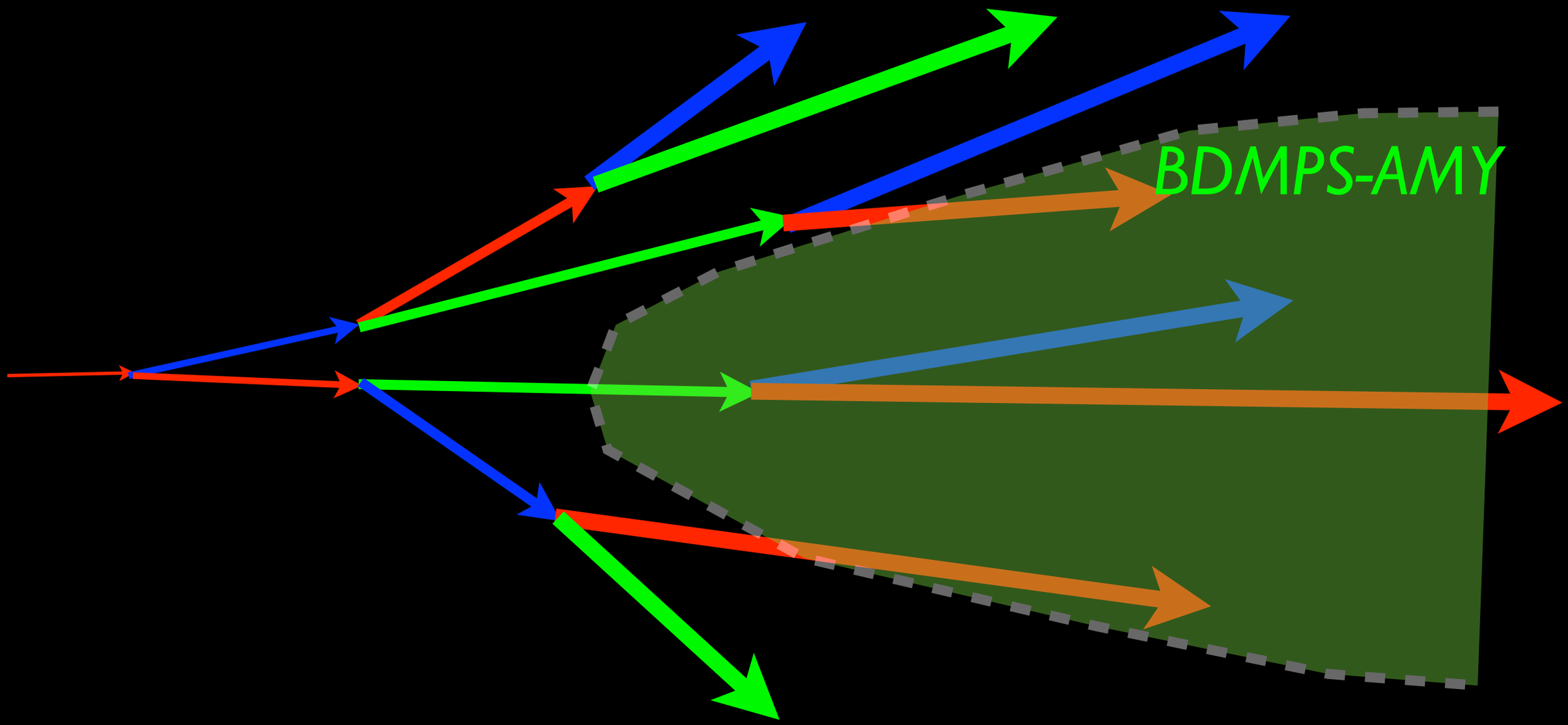

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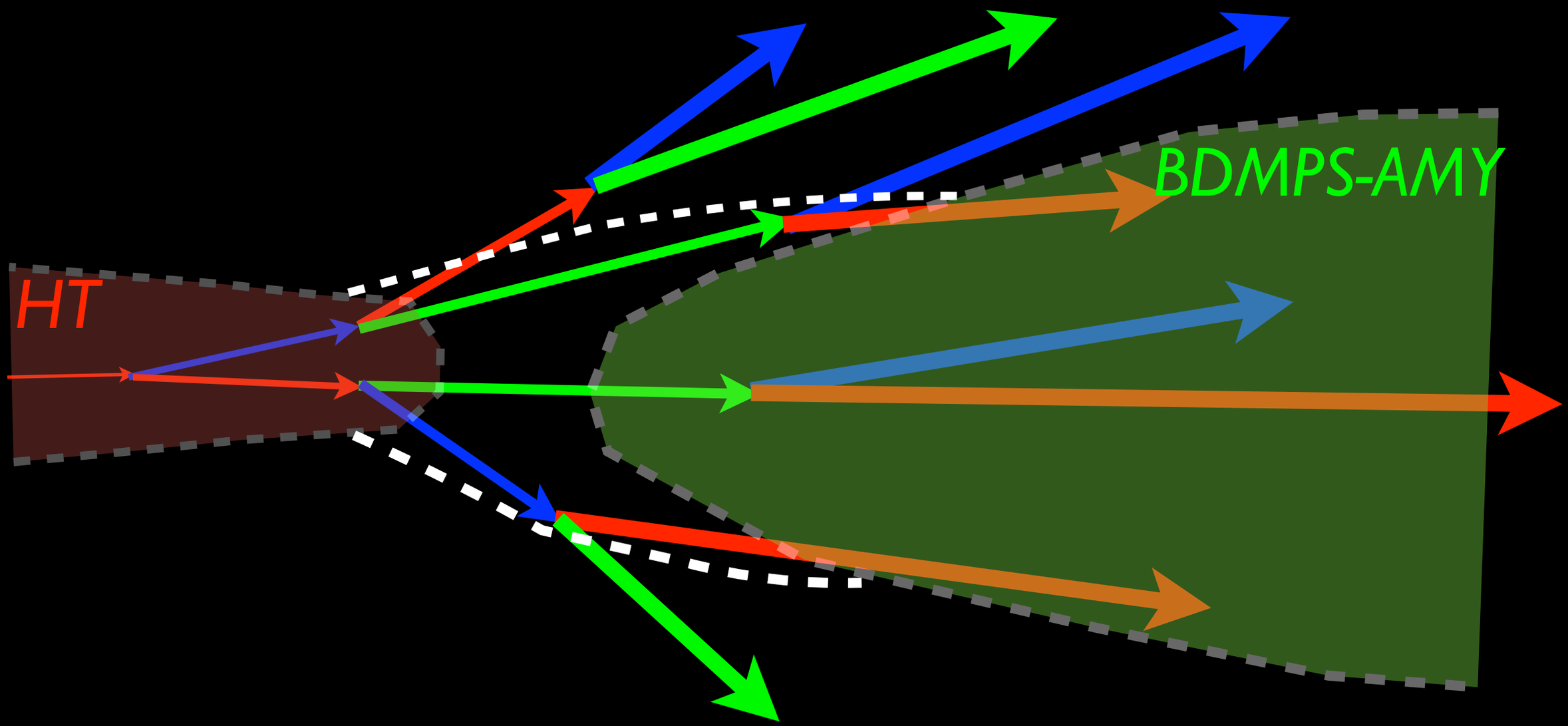

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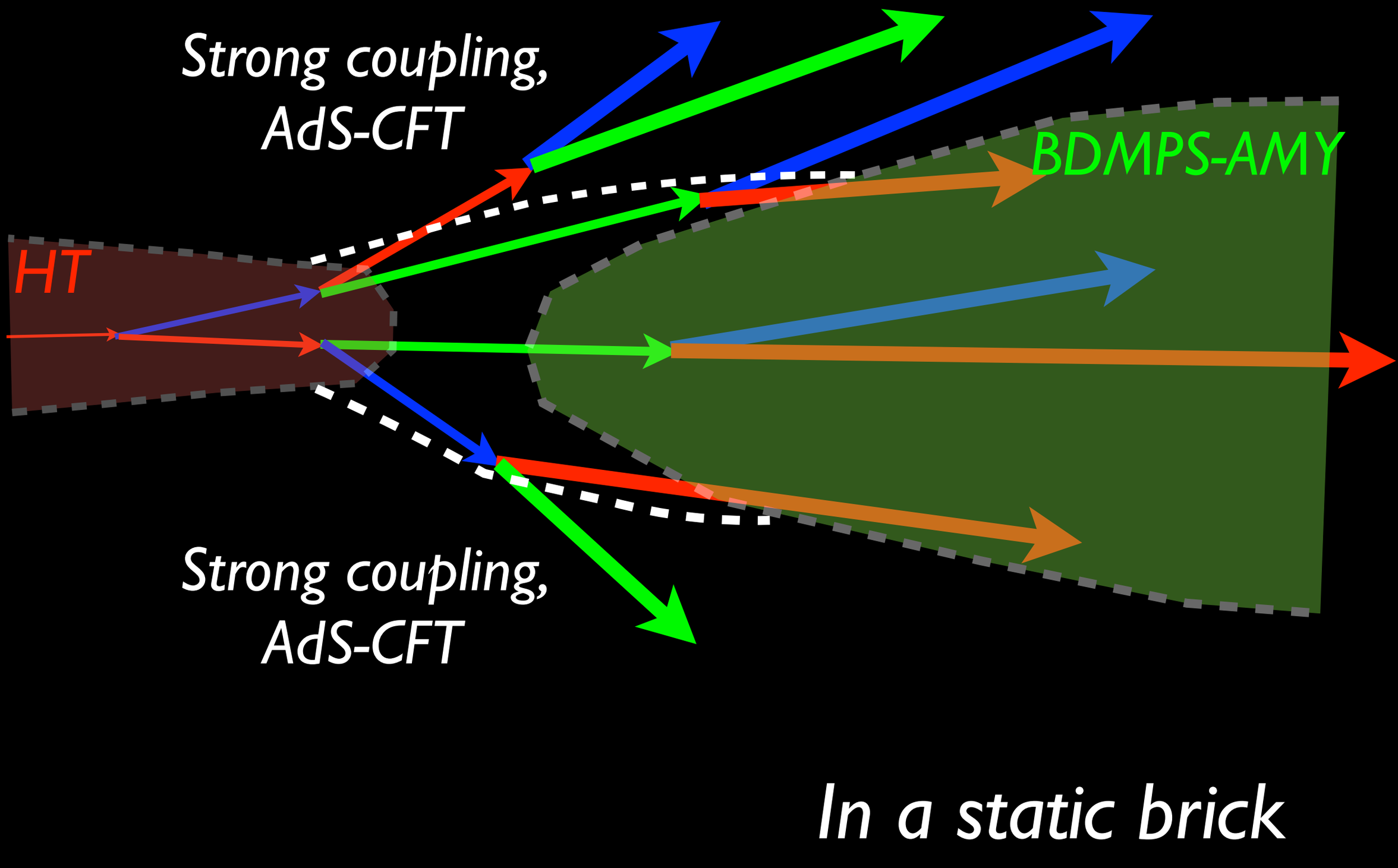

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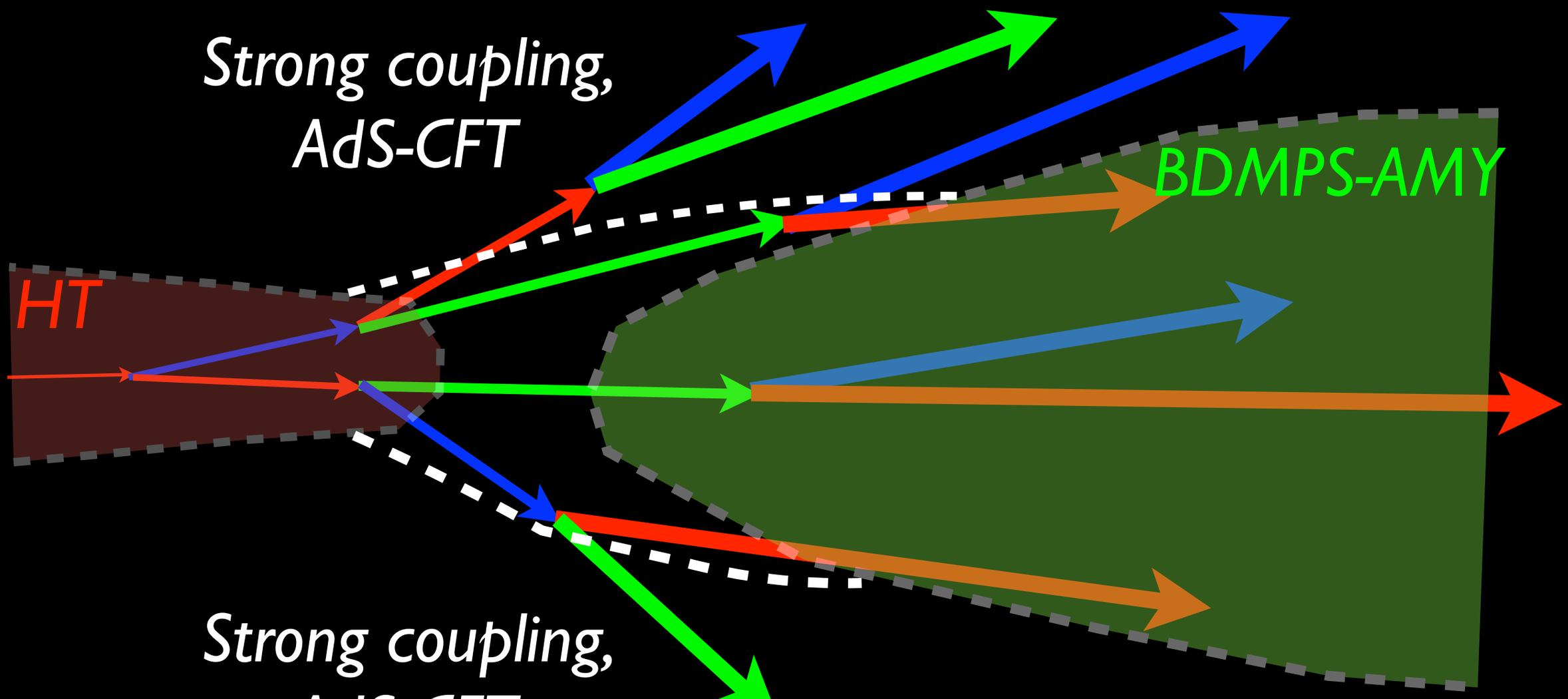

In an expanding QGP

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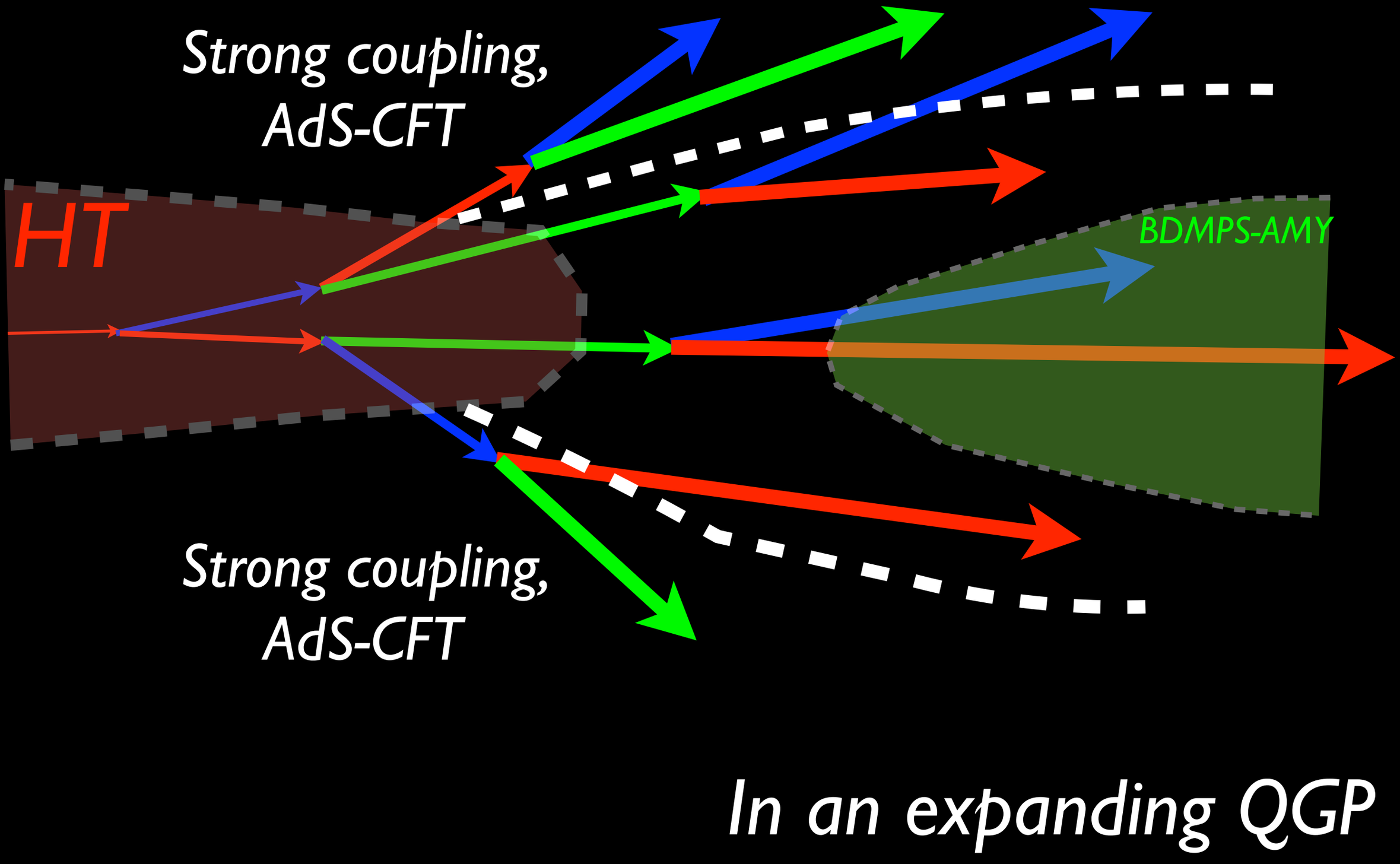
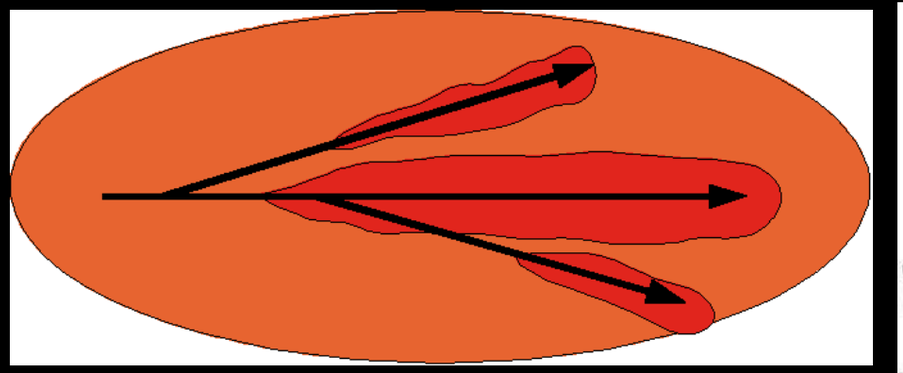


In an expanding QGP

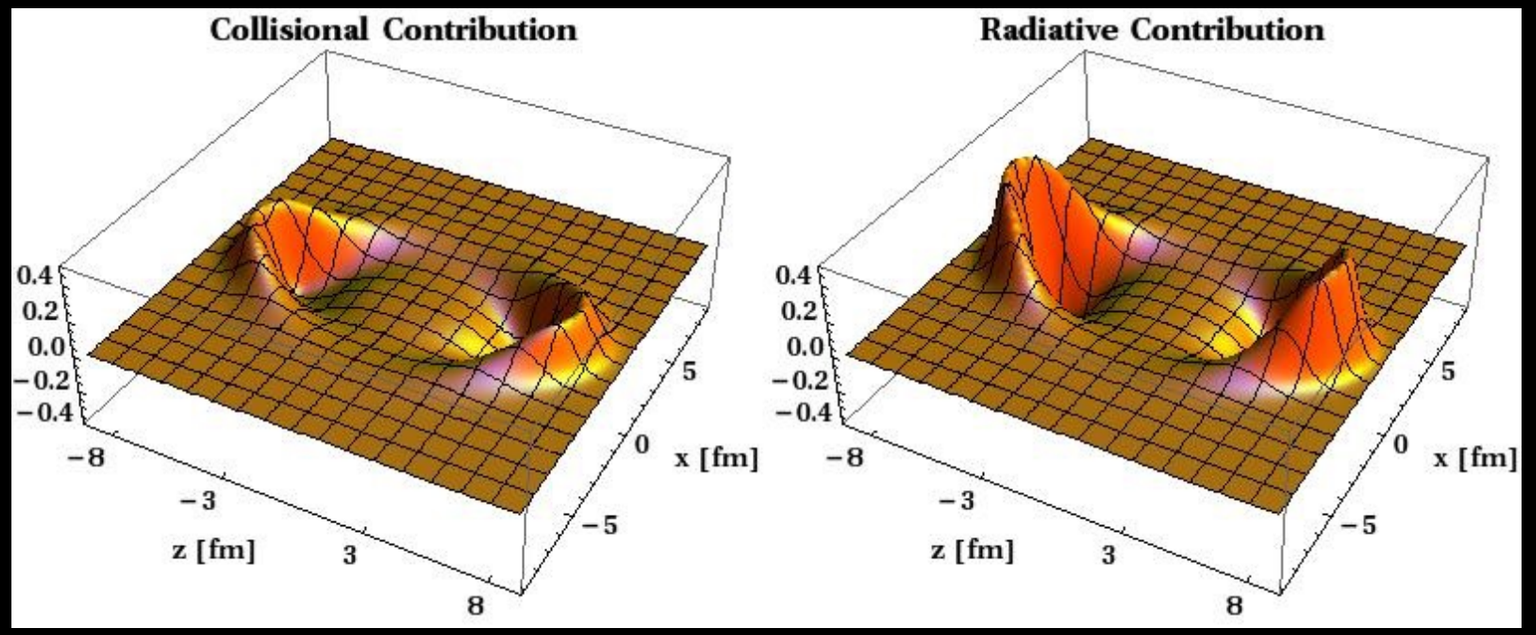
Type II transport coefficients

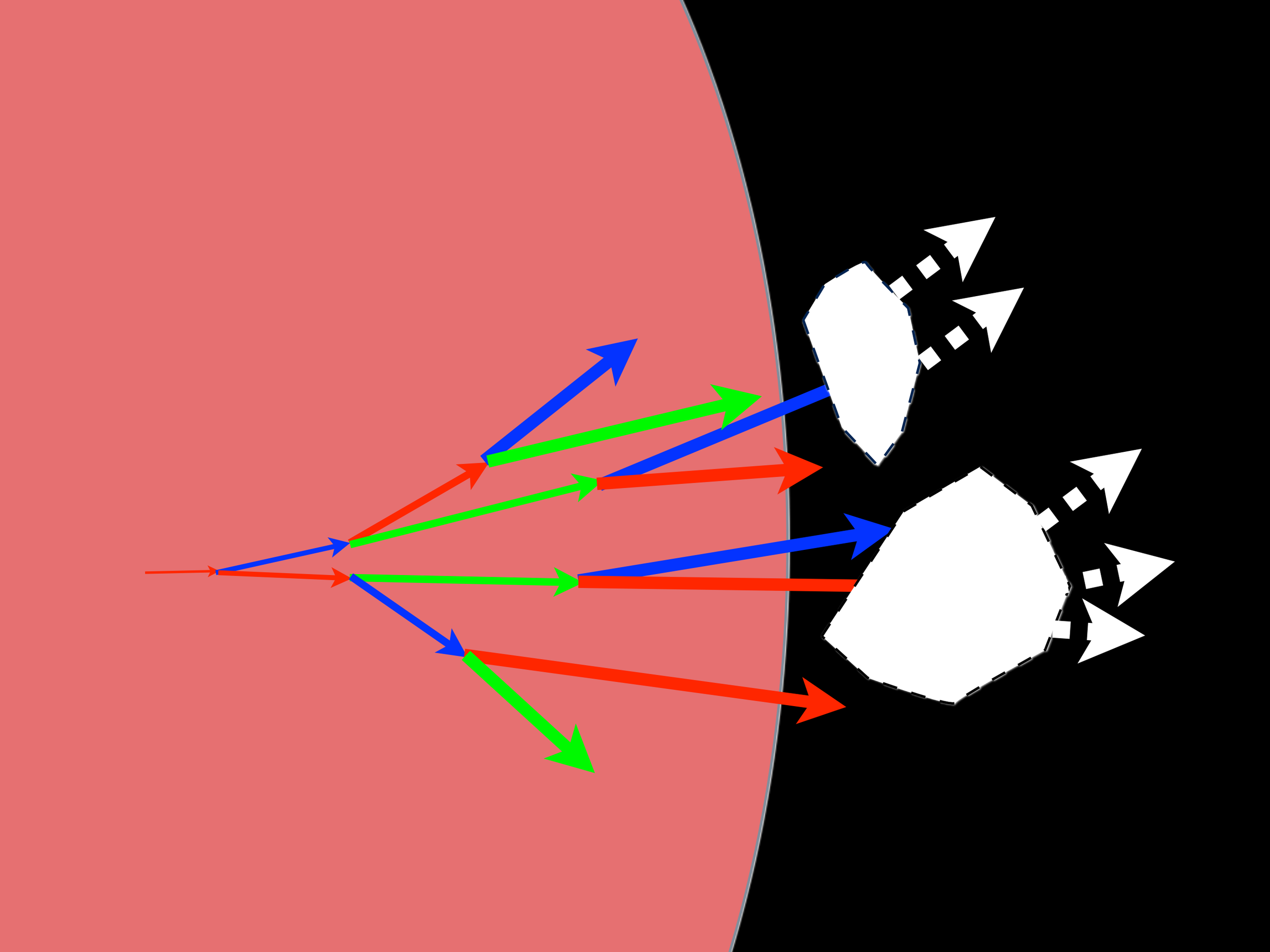
- Should be calculable directly in AdS/CFT.
- or any phenomenological model of the medium
  e.g., MARTINI, CCNU-LBNL, JEWEL
- Will be greatly enhanced by perturbative splits

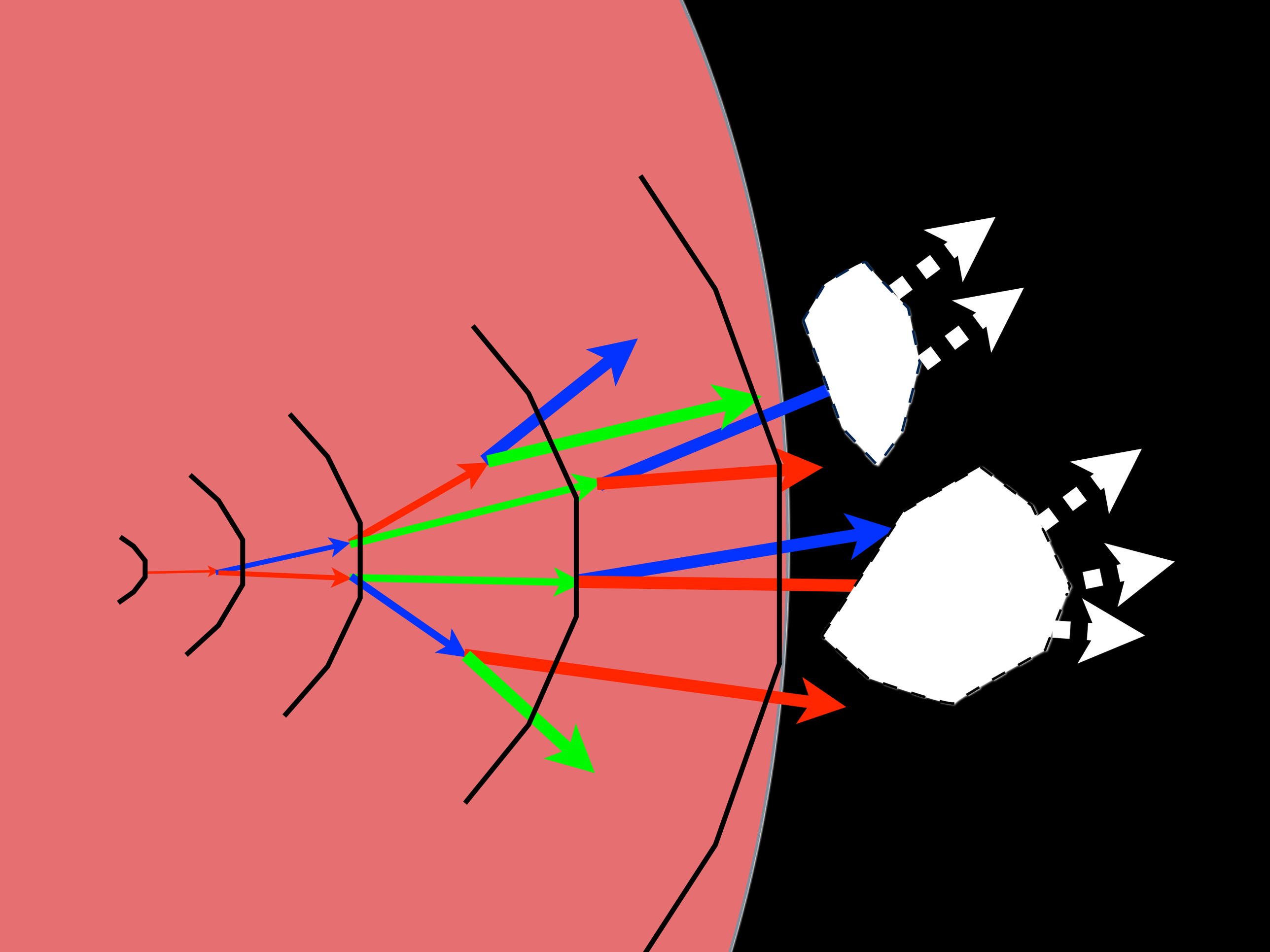
- Directly connected to thermalization of energy in medium



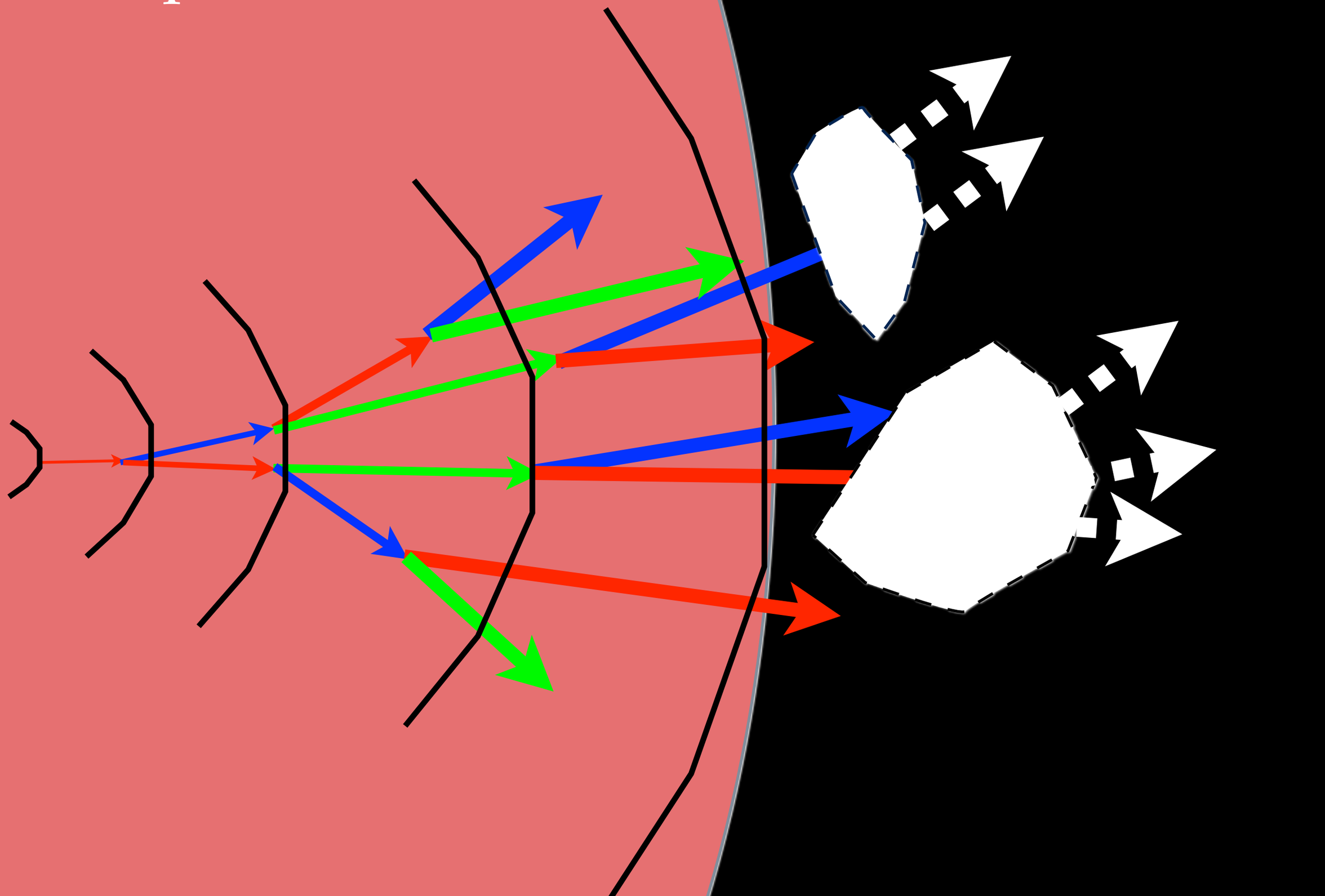
B. Neufeld & B. Muller,
G-Y.Qin, AM, H. Song and U. Heinz







The modification of the underlying medium depends on these new coefficients



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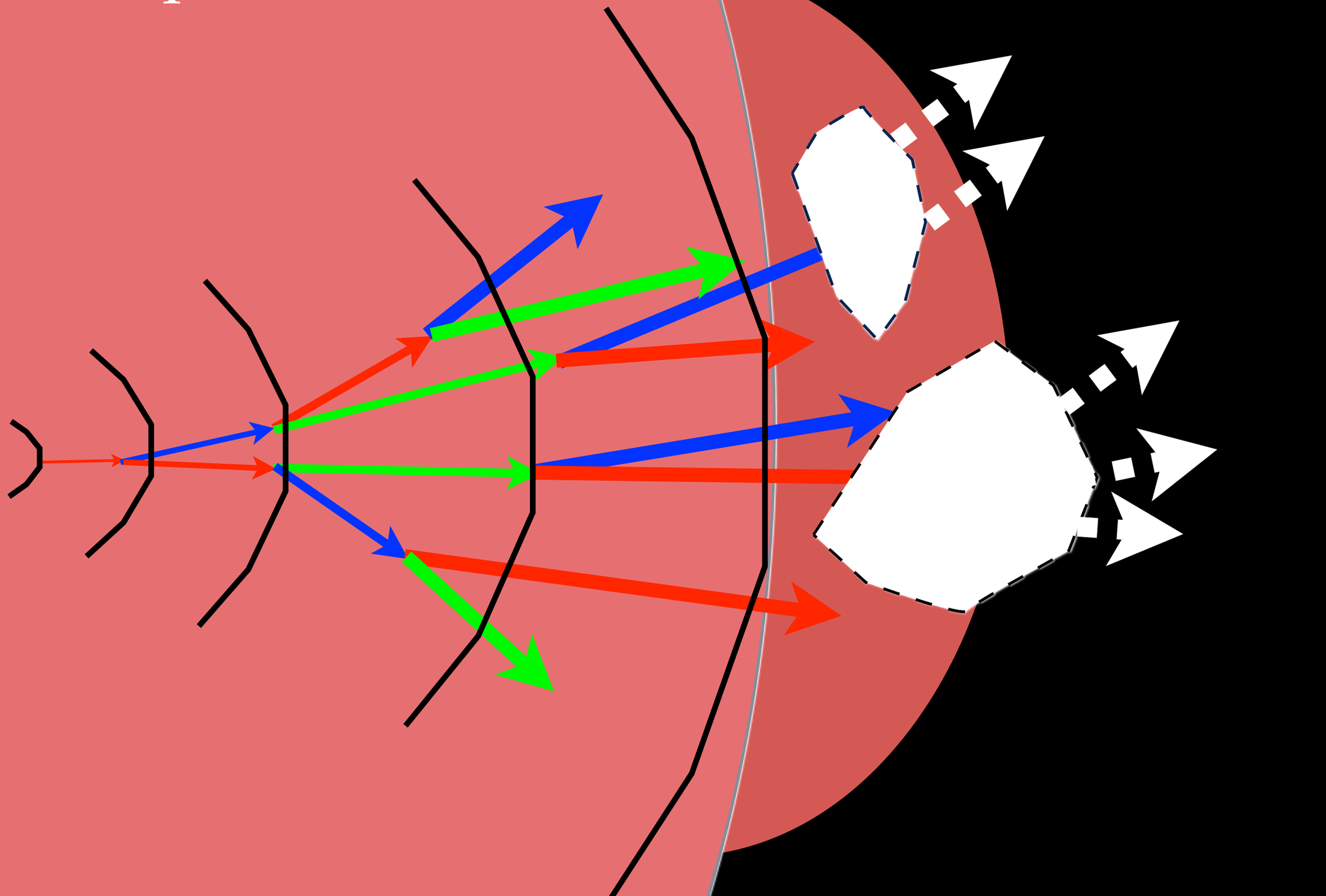
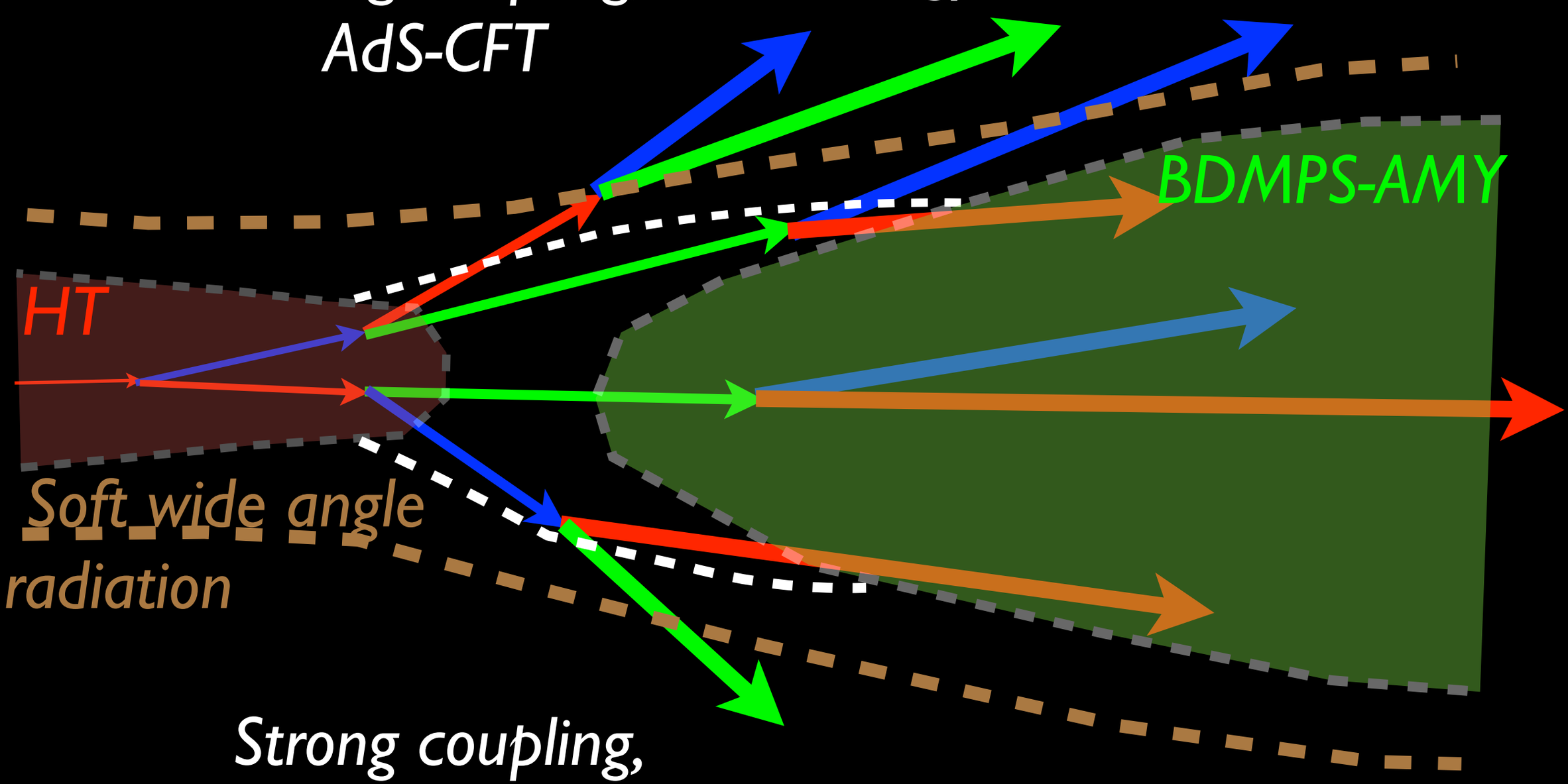


Hadronization: still not resolved, Need a dependable model

Strong coupling, AdS-CFT

Energy thermalization



Fries, Ko,

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Strong coupling, AdS-CFT

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HT

BDMPS-AMY

Hadronization

Soft wide angle radiation

Strong coupling, AdS-CFT

Energy thermalization

Fries, Ko,

Heavy-quarks and more issues

- *Heavy quarks have a whole new phase, due to the dead cone effect*

- *A ``Gunion-Bertsch'' phase with scattering and emission in tandem*

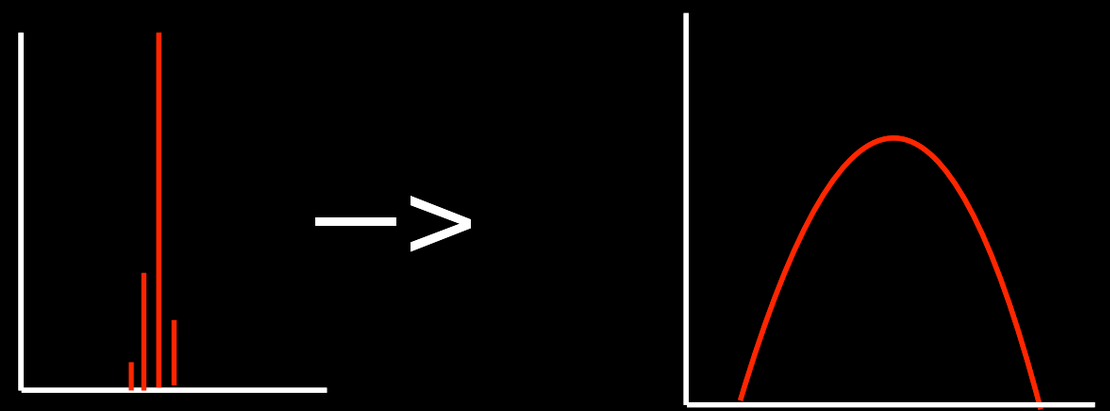
- *Also due to mass, depend on a different range of x from the QGP-PDF*

$$\hat{q} = \frac{4\pi^2 C_R \alpha_s}{N_C^2 - 1} \int \frac{dy^-}{\pi} \frac{\rho}{2p^+} \langle A | F_\perp{}^+(y^-) F^{\perp +}(0) | A \rangle \, e^{-i\bar{\Delta} P^+ y^-},$$

Summary

- Jets are a window to both static and dynamic properties of the QGP
- These are revealed through type 1 and type 2 transport coefficients
- The effect of Type 2 depends on the magnitude of type 1
- Hadronization in the presence of a medium complicates all phenomena
- S-PHENIX will allow for wide range of kinematics at lower temperatures close to the phase transition
- In order to extract the maximal amount of information from S-PHENIX and LHC program, next gen. MCs need to be in place.

On becoming a regular source term, effects can be calculated by hydro

$\delta T^{\mu\nu}$ 

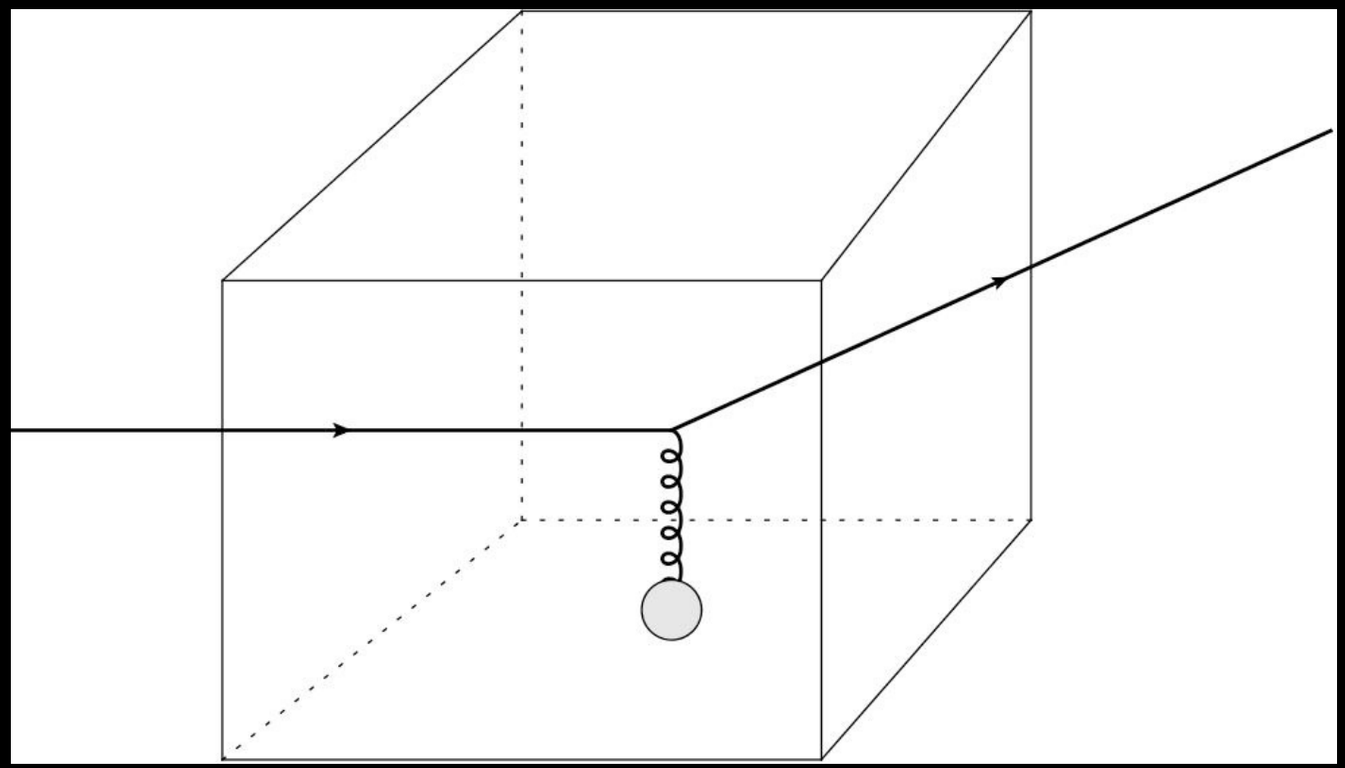
The energy deposited over a region is known

Width of energy distribution at time δt *after parton*$=\delta w_e$

A dimensionless coefficient $W = \frac{\delta w_e}{\delta t}$

Can go beyond this with skewness and kurtosis etc.
Also need vectorial coefficients for momentum

$\hat{q}$ is a lot more than just a number



$$W(k_\perp) = \sum_X \langle q; M|\mathcal{M}^*|q + k_\perp; X\rangle\langle q + k_\perp; X|\mathcal{M}|q; M\rangle$$

$$\mathcal{M} = \int d^4x g\bar{\psi}(x)\not{A}(x)\psi(x)$$

in terms of W, we get

$$\hat{q} = \sum_k k_\perp^2 \frac{W(k)}{t},$$

Energy deposition-thermalization